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Storm Water Management Model Verification - Hamilton Test Catchment Research Report No. 99



**Research Program for the Abatement of Municipal Pollution
under Provisions of the Canada-Ontario Agreement
on Great Lakes Water Quality**

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RESEARCH REPORT

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies being carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of Environment, and contracts with municipalities, research institutions and industrial organizations.

The Scientific Liaison Officer for this project was Mr. J. Marsalek, Environment Canada.

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STORM WATER MANAGEMENT MODEL
VERIFICATION - HAMILTON TEST CATCHMENT

by

Gore and Storrie Limited
Consulting Engineers

RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
PROVISIONS OF THE CANADA-ONTARIO
AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

A residential test catchment in Hamilton, Ontario, was selected and equipped with a data acquisition system for the collection of rainfall data, and quantity and quality urban runoff data. The test catchment was served by a combined sewer system and comprised an area of 71 ha (176 acres).

The hydrologic and physical characteristics of the watershed, the criteria adopted for the selection of the instrumentation system, its installation and the data collection procedure used are described.

The results of data analysis and the calibration and verification results of the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) are discussed in detail and are presented in tabular and graphical forms. These results confirmed the reliable performance of the SWMM runoff quantity model as indicated by the reasonable agreement of the simulated hydrographs with observed values. On the other hand, the quality model used did not produce acceptable correlation between measured and simulated pollutographs when calibration was attempted on an event basis for some pollution parameters.

RÉSUMÉ

Un bassin versant d'un quartier résidentiel de Hamilton (Ontario) a été équipé, à titre expérimental, d'un système de collecte de données afin de recueillir des renseignements sur les pluies ainsi que sur la quantité et la qualité du ruissellement urbain. Ce bassin était desservi par un système d'évacuation unitaire et couvrait une superficie de 71 ha (176 acres).

Les caractéristiques hydrologiques et physiques du bassin, les critères de sélection de l'appareillage, son installation et la méthode d'acquisition des données sont décrits.

Les résultats de l'analyse des données et ceux de l'étalonnage et de la vérification du Modèle de gestion des eaux pluviales de l'Agence américaine de protection de l'environnement sont comparés et examinés de façon détaillée et présentés sous forme de tableaux et de graphiques. Ils confirment la fiabilité du modèle, du point de vue quantitatif, car les quantités relevées lors des expériences correspondent d'assez près à celles des hydrogrammes de simulation. Par contre, sur le plan de la qualité des eaux, les essais d'étalonnage du modèle utilisé, en fonction de certains paramètres de pollution examinés individuellement, ont révélé un écart innacceptable entre les résultats obtenus et les "pollutogrammes" de simulation.

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Increasing environmental concerns associated with the pollutant loadings contributed by urban storm water runoff to receiving waters have created the need for reliable impact assessment techniques. In view of the difficulties and monetary constraints which prevent the establishment of extensive field monitoring systems to gather the relevant data, the use of computer-oriented mathematical models of physical systems as alternative cost-effective predictive tools has gained wider acceptance in the United States and in Canada. For the reliable application of these models, they must be calibrated and verified for different types of urban watersheds.

The Storm Water Management Model (SWMM) developed under the sponsorship of U.S. Environmental Protection Agency (EPA) is specifically designed to model urban storm runoff and combined sewer overflow processes [1]. The model has been tested and adapted for Canadian conditions as part of the Canada/U.S. Agreement on Great Lakes Water Quality [2].

As part of the ongoing Research Program for the Abatement of Municipal Pollution under the Canada-Ontario Agreement on Great Lakes Water Quality, this study was commissioned as a pilot project to collect storm runoff quantity and quality data from an urban test catchment and carry out a calibration and verification study of a selected version of SWMM using the collected data as a basis.

The terms of reference for this study were to:

- 1) establish an urban test catchment served by a combined sewer system;
- 2) design, supply, install and operate a data acquisition system in the test catchment for the monitoring of precipitation, temperature, and runoff quantity and quality;
- 3) calibrate and verify the Storm Water Management Model (SWMM), making use of the physical data of the catchment and the event-based data monitored by the instrumentation system;
- 4) report the findings of the study in a report, together with all results, supporting information and recommendations related to future model applications.

In cooperation with the Scientific Authority, the National Water Research Institute, Canada Centre for Inland Waters, an urban test area was selected in Hamilton, Ontario. This test catchment was subsequently instrumented and rainfall/runoff data were collected through the period of October 1975 to November 1976, and from July 1977 to October 1977. The dry weather flow was also sampled during the fall of 1976 and in February and March 1978 to establish the sources of the pollutant loadings in the storm runoff.

This report contains a complete description of the study area and the installed instrumentation. It also describes the operation of the data acquisition system, the data collection and analysis, and the verification of the SWMM by means of selected events. A number of conclusions and recommendations are made regarding the performance of the SWMM and potential improvements. A few recommendations are included for future studies involving data collection and analysis.

Most of the collected data, as well as the results of selected simulations, were condensed and refined and are included in appendices referred to in this report. The appendices are available as a separate volume from the Scientific Authority for the project, Mr. J. Marsalek, P. Eng., of the National Water Research Institute, Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario.

2 DESCRIPTION OF TEST CATCHMENT

2.1 Location and General Description

The study area was in the City of Hamilton at the west end of Lake Ontario, approximately 60 km (38 miles) southwest of Toronto. Hamilton is divided into two parts by the Niagara Escarpment, with the downtown core area in the lower section of the city. The study area selected for instrumentation was located on Hamilton Mountain, above the escarpment, in the southeastern part of the city, as shown in Figure 1. The 71-ha (176-acre) area drains into the main sewer along Upper Kenilworth Avenue which connects to the Fennell Avenue trunk.

The section of the study area south of Mohawk Road, comprising 16.6 ha (41 acres), was disconnected from the total test watershed at the end of 1976. The connection had been only temporary, pending new development and the availability of a new outlet. Thus, the acreage of the test catchment for the 1977 data collection period was reduced to 54.7 ha (135 acres).*

The population of the initial (total) test catchment was estimated as 3050, with a density of about 54 persons per ha based on planning information for different neighbourhood areas.

The average dry weather flow was estimated to be about 16 L/s (0.56 cfs) from field measurements.

2.2 Catchment Topography

The overall surface drainage on the test catchment is towards Upper Kenilworth Avenue which is a north-south street located close to its eastern boundary*. The southwestern corner has the highest elevation which is about 198.2 m (650 feet). The lowest elevation, about 187.5 m (615 feet), occurs at two locations along Upper Kenilworth Avenue; one is at the southern boundary and the other is at the intersection with Broker Drive. In general, the average ground slope is about 0.3% except at the southwest corner where it is relatively steep at an average slope of 2%.

* Detailed land use zoning plans and a contour map for the test catchment are available from the Scientific Authority at the address given at the end of Section 1.

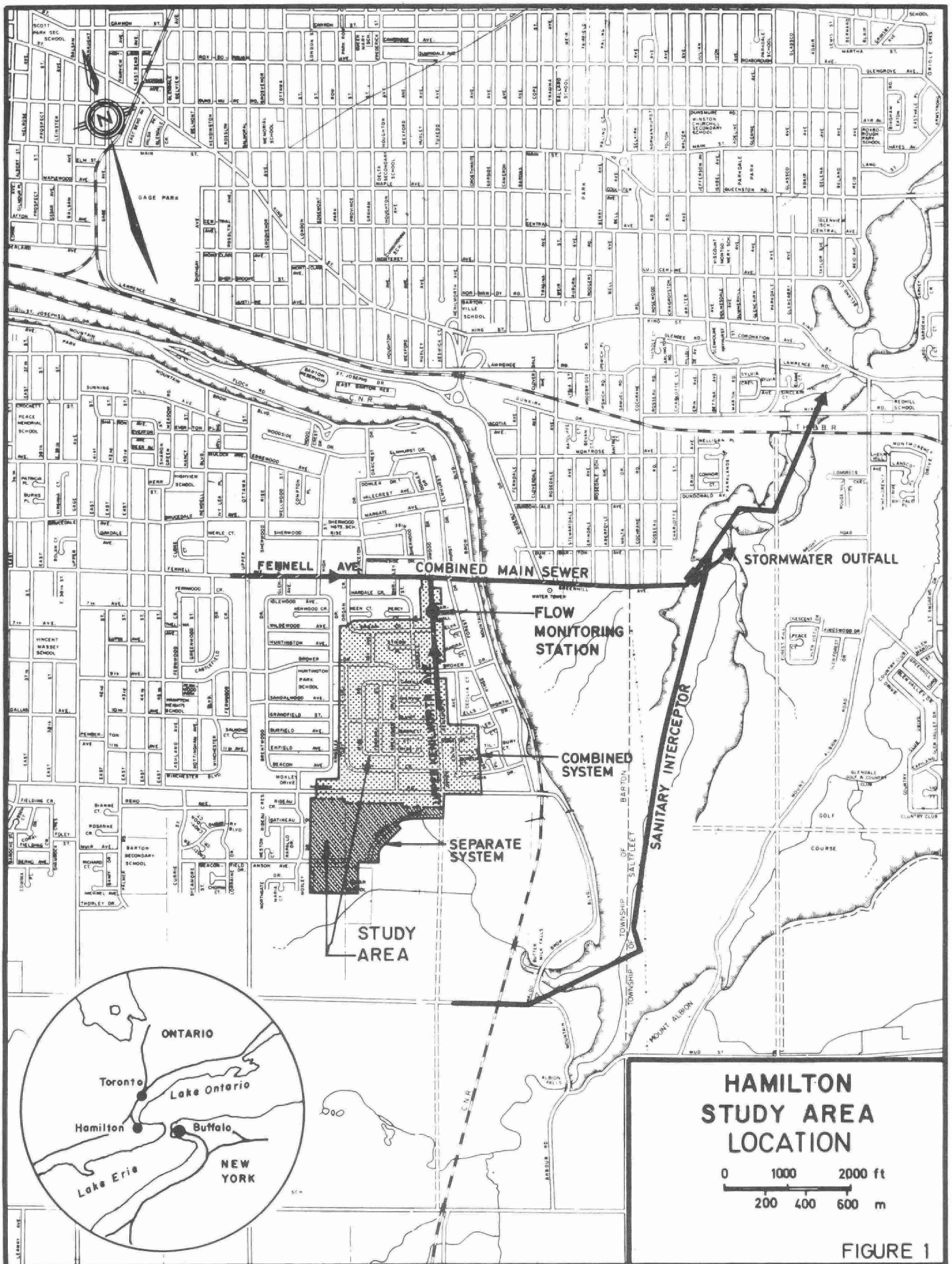


FIGURE 1

2.3 Land Use

The land use on the test catchment is predominantly single-family residential, with a few apartment buildings, semi-detached units, a food chain store with parking area and three schools.

The area north of Mohawk Road was developed in the mid-1950's, while some of the developments south of Mohawk Road were completed in the mid-1960's. The construction of the latest development at the southern boundary, between Mohawk Road and Carson Drive, was carried out during 1976 (May to December).

The extent of the test catchment before and after December 1976 and the corresponding approximate land use percentages were as follows:

Description	Unit	Before	After
		December 1976	
Area of test catchment	hectare (acre)	71.3 (176)	54.7 (135)
Detached homes	percent	70.4	86.5
Semi-detached homes	"	1.5	2.0
Apartment buildings	"	2.5	3.2
Schools	"	6.6	0.0
Commercial	"	1.5	1.8
Open space	"	17.5	6.5
TOTAL	"	100.0	100.0

2.4 Hydrologic Response Characteristics

The three main hydrologic characteristics of a watershed which influence the generation of surface runoff during storm events are: the degree of imperviousness, the depression storage, and the infiltration capacity. A brief description of these parameters as applied to the test catchment is presented below.

2.4.1 Imperviousness

The impervious areas in this residential watershed consist of the roof areas, driveways, parking lots, streets and sidewalks.

Prior to December 1976 (i.e., completion of the new subdivision in the study area) the overall imperviousness was approximately 36%, formed of 32% directly connected impervious areas and 4% impervious areas draining onto pervious ground. The average imperviousness of the reduced watershed after December 1976 increased to 41% due to the disconnection of a large part of the pervious area.

The following details apply to the watershed for the pre-December 1976 period:

- The sidewalks were mostly not separated from the streets except for the major thoroughfares and, therefore, drained directly to the gutters.
- The total area of roads and sidewalks within the watershed was 10.25 ha (25.34 acres), not including the sidewalks separated from the roads, which were another 0.75 ha (1.84 acres).
- The total gutter length was 17.10 km (10.62 miles), for a total road length of 8.55 km (5.31 miles), of which 2.44 km (1.51 miles) were major through roads as follows:

Upper Kenilworth Avenue	-	1.143 km (0.710 miles)
Broker Drive	-	0.500 km (0.310 miles)
Mohawk Road East	-	0.795 km (0.495 miles)

- Part of Carson Drive south of Mohawk road was left unpaved during the period prior to December 1976, but with catch basins in place. Hence the catch basin inlet openings were above the road levels, causing significant street detention locally during a rainfall before overflowing into the sewer system. Therefore, this road was modelled as a separate subcatchment with modified detention and infiltration values and zero imperviousness.
- While most of the front yards drained towards the roads with slopes of 2% to 10%, no backyard drainage system was observed, either on the plans or during field surveys. It was reported that heavy rainfall causes temporary ponding in some backyards.

2.4.2 Depression storage

Field inspection of the impervious areas and study of plans showed that the potential for depression storage in the parking lots, on the road pavements and on the flat roofs of the food stores and apartment buildings could be significant. The roofs of single-family units have conventional slopes inducing only an initial wetting loss.

For the pervious areas, depression storage varied considerably from the "natural" area between Mohawk Road, Carson Drive and the school in its development state, to the well-kept playgrounds around the schools with short-cut grass and uniform grading. Most of the front-yards and backyards were also well-graded and maintained to minimize ponding.

2.4.3 Ground infiltration capacity

Most of the upper Hamilton area above the Niagara Escarpment has a shallow clayey cover over flat, fissured limestone layers. Since the study area was located above the escarpment, the above-noted geological formation was predominant and was expected to influence the infiltration characteristics of the pervious surface. Other factors affecting the infiltration capacity are the type of soil, vegetation, slope and the maintenance of the pervious surface. The actual ground infiltration capacity and its variation had not been monitored or measured for this area.

The hydrologic characteristics of the study area are further dealt with in the presentation and discussion of the observed and simulated results (Sections 5 and 6).

2.5 Sewer System

The sewer system in the section of the catchment north of Mohawk Road is of the combined type, while the section south of Mohawk Road is serviced by a separate sewer system. Figure 1 shows the general layout and flow directions of the external receiving sewer system and the sewer network in the study area.

Within the study area, the collector sewers drain into the main trunk sewer on Upper Kenilworth Avenue which drops at its northern end (at the study area boundary) into the Fennell Avenue combined trunk sewer. This Fennell Avenue trunk sewer discharges into Red Hill Creek through a

a regulator chamber which diverts the sanitary flow into the Red Hill Creek sanitary interceptor. The regulator is designed to shut off the inflow to the interceptor once storm water overflows begins. In December 1976, the separate sewer system draining the area south of Mohawk Road was disconnected from the above system by diverting the Carson Drive trunk storm sewer to the south along Upper Kenilworth Avenue.

Most of the sewers have been cut into the horizontally layered limestone rock formation as the clayey overburden is quite shallow. It is conceivable that the fractured rock formations combined with shallowness of the overburden and the use of trenches cut into the rock for laying sewers significantly increases the potential for infiltration into the sewers through sewer joints and cracks, especially during prolonged wet weather. Such infiltration would change the base flow in the sewer system from one rainfall event to the next, depending on the antecedent rain and the intervening dry days.

The combined systems were constructed in the mid-1950's while the separate sewers were added in the mid-1960's. The Kenilworth trunk sewer north of Elliot Avenue is built in a tunnel with local sewers installed parallel to connect the house laterals and catch basins. Most sewers are concrete; some smaller ones are of vitrified clay.

All the foundation drains are connected to the sewer system. In the case of the southern area served by the separate sewer systems, the details of these connections had not been determined. This was not crucial to this study, which was based on the initial total area that drained into the Upper Kenilworth trunk sewer. The average catch basin density is one inlet for every 80 m (260 feet) gutter length. Most of the catch basins have both gratings and curb inlets.

The cross-section of the tunnel sewer is of basket-handle shape with a triangular bottom and is 120 cm wide by 150 cm deep (4 feet x 5 feet) with a free flow capacity of $3.5 \text{ m}^3/\text{s}$ (125 cfs). The rest of the sewers are circular, with diameter range of 300 to 1200 mm (12 to 48 inches). Most pipe slopes are less than one percent with a few exceptions. The minimum slope is 0.3 percent. The Manning's coefficient of roughness was assumed to be 0.013 for all sewers as an average value.

The conduit system length is 9004 m (29 540 ft) or 126.3 m/ha (168 ft per acre). The volumetric capacity of the system is 3295 m³ (116 290 ft³), or an average of 46 m³/ha (660.7 ft³ per acre) disregarding the capacities of the catch basins and manholes.

2.6 Street Maintenance Data

The Department of Engineering of the regional municipality provided the following street sweeping frequencies in the test catchment:

Upper Kenilworth Avenue, Mohawk Road	- once per week
All others	- once per month

Spreading of de-icing materials in winter follows a similar pattern with Upper Kenilworth Avenue and Mohawk Road getting about 800 kg/km (2800 pounds per mile) and the local roads about 200 kg/km (700 pounds per mile) of sodium chloride on a typical day. Specific information on catch basin and sewer cleaning schedules were not readily available.

2.7 Meteorological Data

The temperature and precipitation data were obtained from the Atmospheric Environment Service (AES), Environment Canada publication "Temperature and Precipitation 1941-1970 - Ontario".

The following mean values were produced by averaging the values of four stations within the Hamilton area:

Average yearly high temperature	=	13.2°C (55.8°F)
Average yearly low temperature	=	3.6°C (38.5°F)
Average yearly temperature	=	8.3°C (46.9°F)
Average yearly precipitation	=	816.9 mm (32.16")

The prevalent yearly wind direction as determined from 1974 records at the Royal Botanical Gardens is southwesterly for ten months, with a mean wind speed of 13.4 km/h (8.3 mph). The harbour location gives a slightly higher wind speed with westerly direction.

3 INSTRUMENTATION FOR FIELD DATA COLLECTION

3.1 General Criteria

With the ultimate objective of field verification of the quantity and quality simulation subroutines for the Storm Water Management Model, the key elements of the required field data acquisition system included:

- rain gauge,
- flow metre,
- sampler and
- recording facilities (e.g., chart recorder).

During the evaluation of several products in connection with the assessment of prospective monitoring locations, it became evident that the selection of a suitable monitoring package was site-specific. The key selection criteria for instrumentation required for this study were, briefly, accuracy of sensing and recording, repeatability of records, reliable performance under adverse weather conditions such as freezing, ability to conform to the requirement for continuous monitoring, ability to cover as wide a range of values as possible from dry to wet weather conditions, and ability to satisfy the vital necessity of providing synchronized data sets for each monitored event. The rainfall and flow data monitoring and recording system, and the sample collecting system as used in the present study, are briefly described in the following sections.

3.2 Instrumentation Set-Up

To obtain flow data and samples representative of the contributions from the study area, the monitoring location had to be at the downstream end of the Upper Kenilworth Avenue trunk sewer. To satisfy this requirement and minimize access difficulties, a manhole on the trunk sewer about 30 m (100 ft) north of Marshall Avenue close to the northern boundary of the study area was selected as the flow monitoring and sample collecting station. One rain gauge and a temperature sensor were installed very close to the monitoring station and all the corresponding recording instruments were placed in a nearby building (to reduce time lag effects on the records). This was achieved through an agreement reached with a nearby homeowner to use part of his garage and obtain the required

power from his house supply. The layout details of the monitoring station are shown in Figures 2 and 3; Figure 4 is a schematic of the electrical circuitry connecting the instrumentation.

A second rain gauge was installed within the study area to the south of the monitoring station and northeast of the Grenadier Road and Mohawk Road east junction to obtain additional precipitation data.

3.3 Rainfall Rate

The two rain gauges were of the tipping bucket type; for each one-hundredth of an inch of rainfall, the bucket tips and empties producing an electrical impulse. This electrical impulse is then converted to a direct rainfall intensity signal through a pulse-rate-to-analog converter by differentiation with respect to the pulse interval, and recorded. While the rain gauge (local rain gauge) at the monitoring station was synchronized with the flow depth and temperature recorders, the other rain gauge (the remote rain gauge) had an independent recorder.

3.4 Flow Rate

The flow measuring devices were located inside the sewer system by accessing through a manhole. A specially-designed modified V-notch with an open throat was installed across the sewer as the measuring weir (Figures 5 and 6). This weir design was adopted to meet the site conditions such as the special shape of the sewer cross-section, and the need to reduce the danger of siltation behind the weir (i.e., to reduce the adverse influence on quality samples during wet weather).

At the hydraulics laboratory of the Canada Centre for Inland Waters, a 1:3 scale of the weir was calibrated with the approach channel and its downstream section modelled to simulate actual flow conditions in the downstream sewer. Even the drop connection of the local sewer was modelled and was found to exert negligible influence on the flow depths. The invert slope of the channel was taken from "as constructed" plans and verified in the field. The rating curve of the weir is shown in Figure 6.

The water level was monitored by a bubbler type instrument. The sensing line was installed 2.5 m (8 ft) upstream from the weir at the wall of the channel. During its operation, the back pressure created by the depth of water is transformed into a proportional electrical current

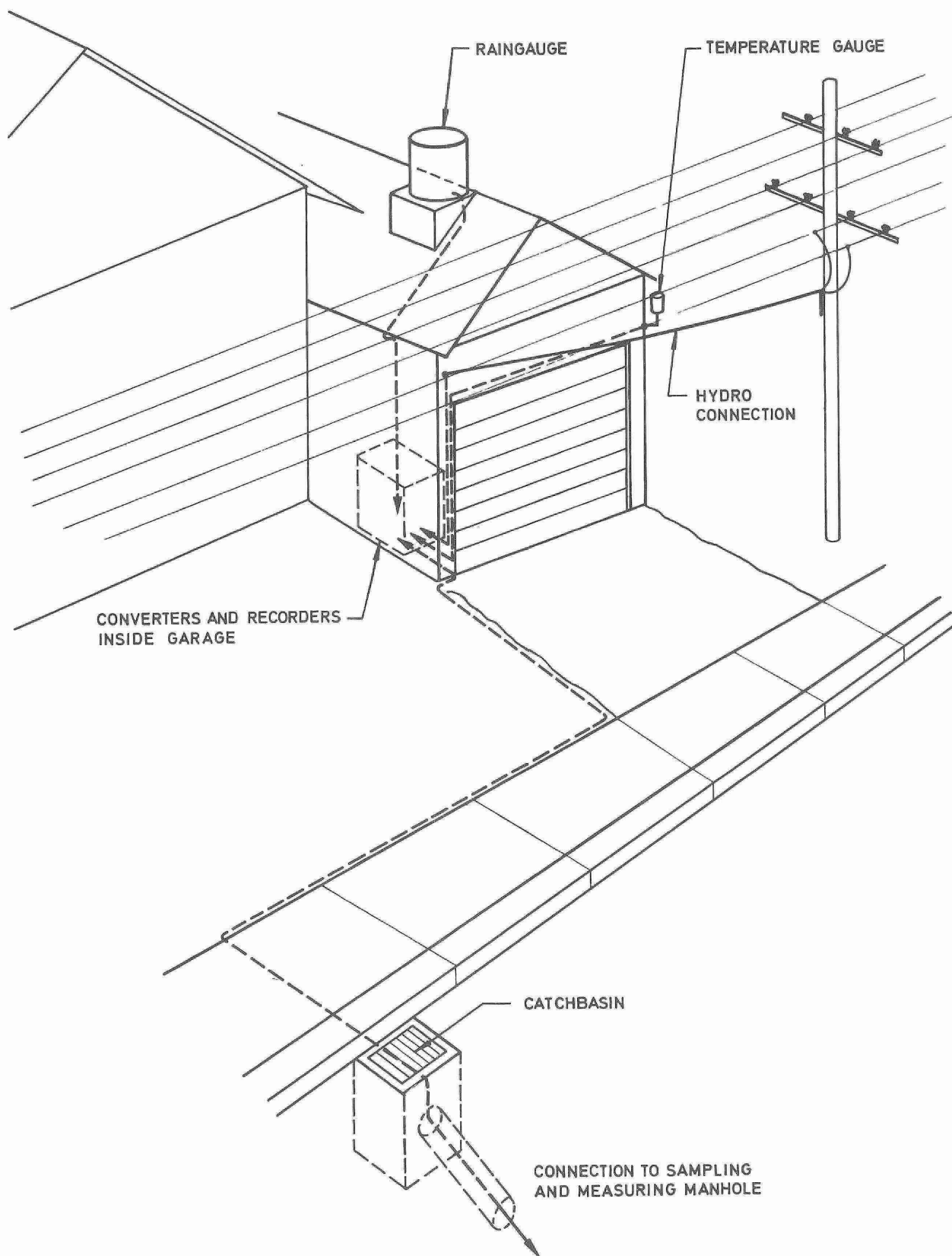


FIGURE 2. INSTRUMENTATION SCHEMATIC - SURFACE DETAILS, PERSPECTIVE VIEW

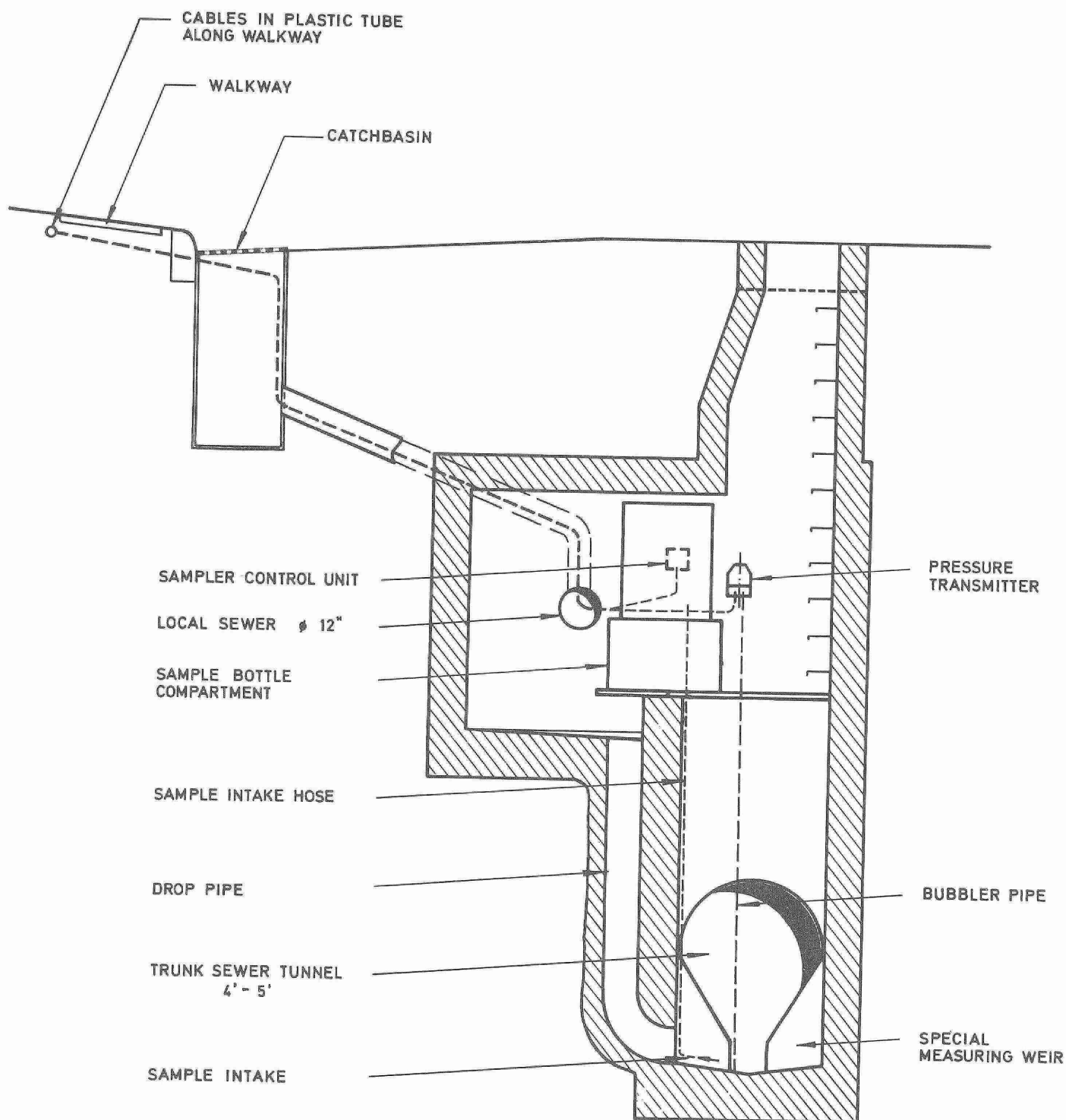


FIGURE 3. INSTRUMENTATION SCHEMATIC - SECTIONAL VIEW OF MANHOLE

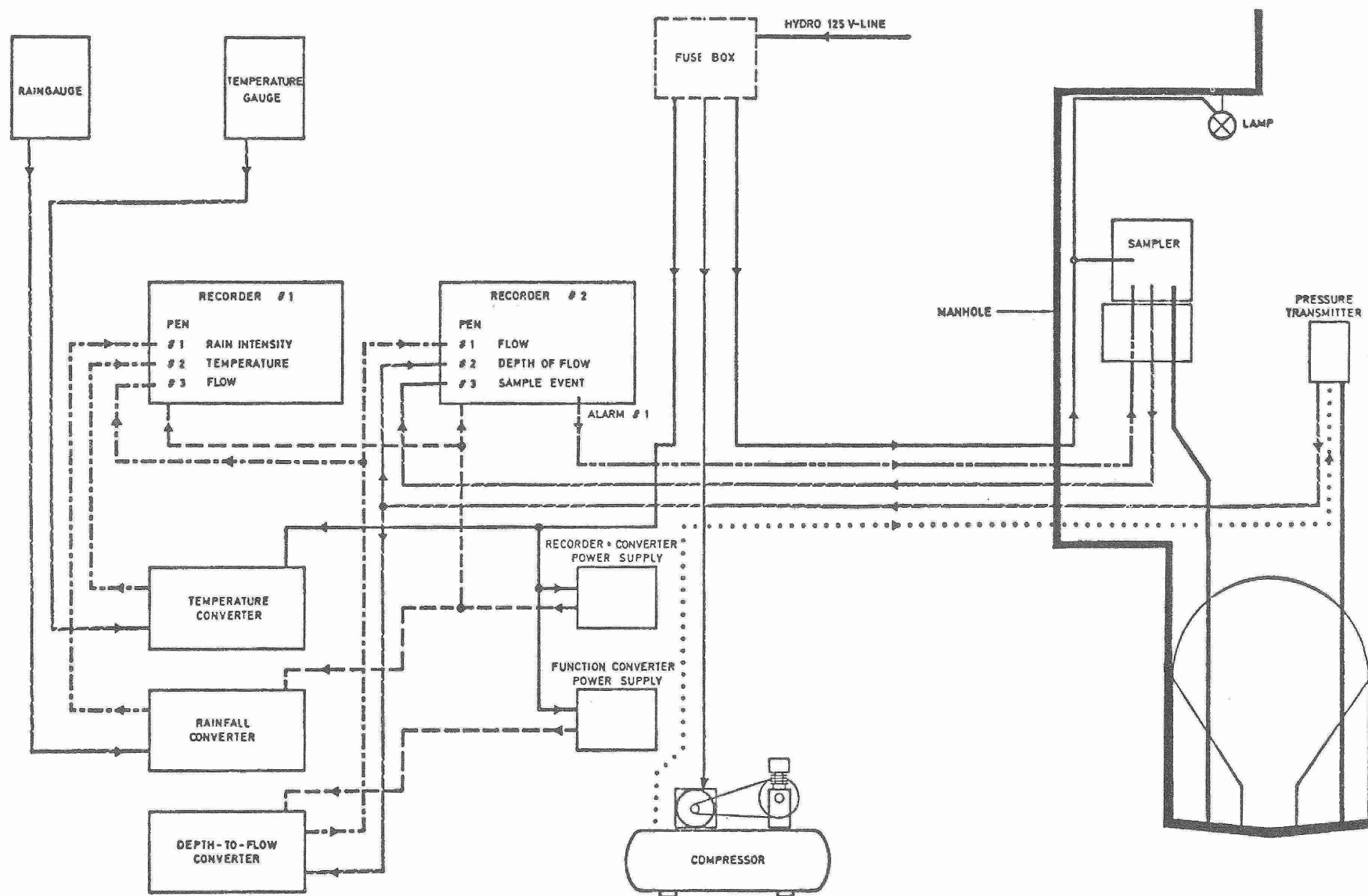


FIGURE 4. INSTRUMENT INTERCONNECTION DIAGRAM

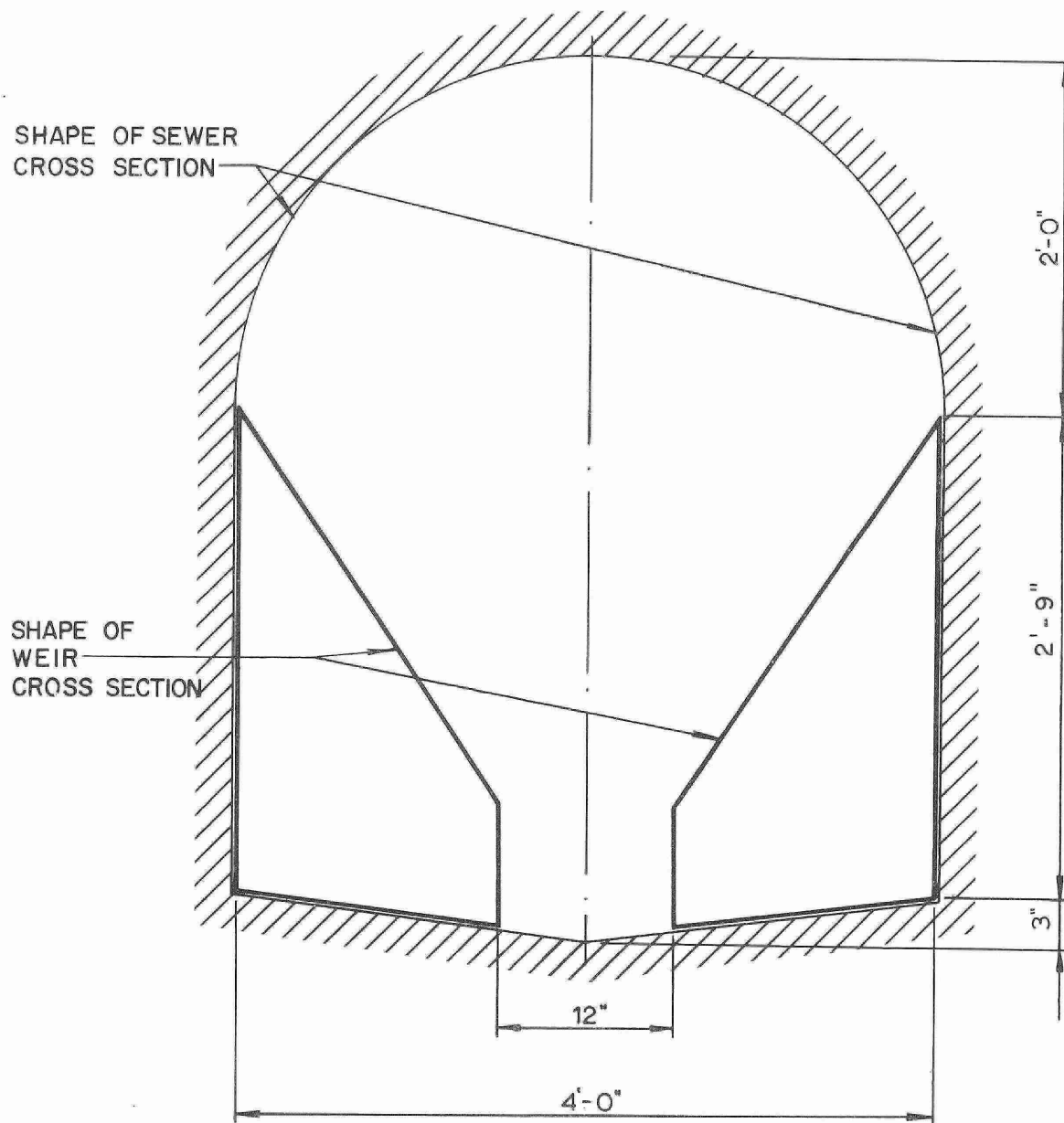


FIGURE 5. SCHEMATIC OF SEWER CROSS SECTION SHOWING WEIR CONSTRUCTION
(Modified V-Notch Weir)

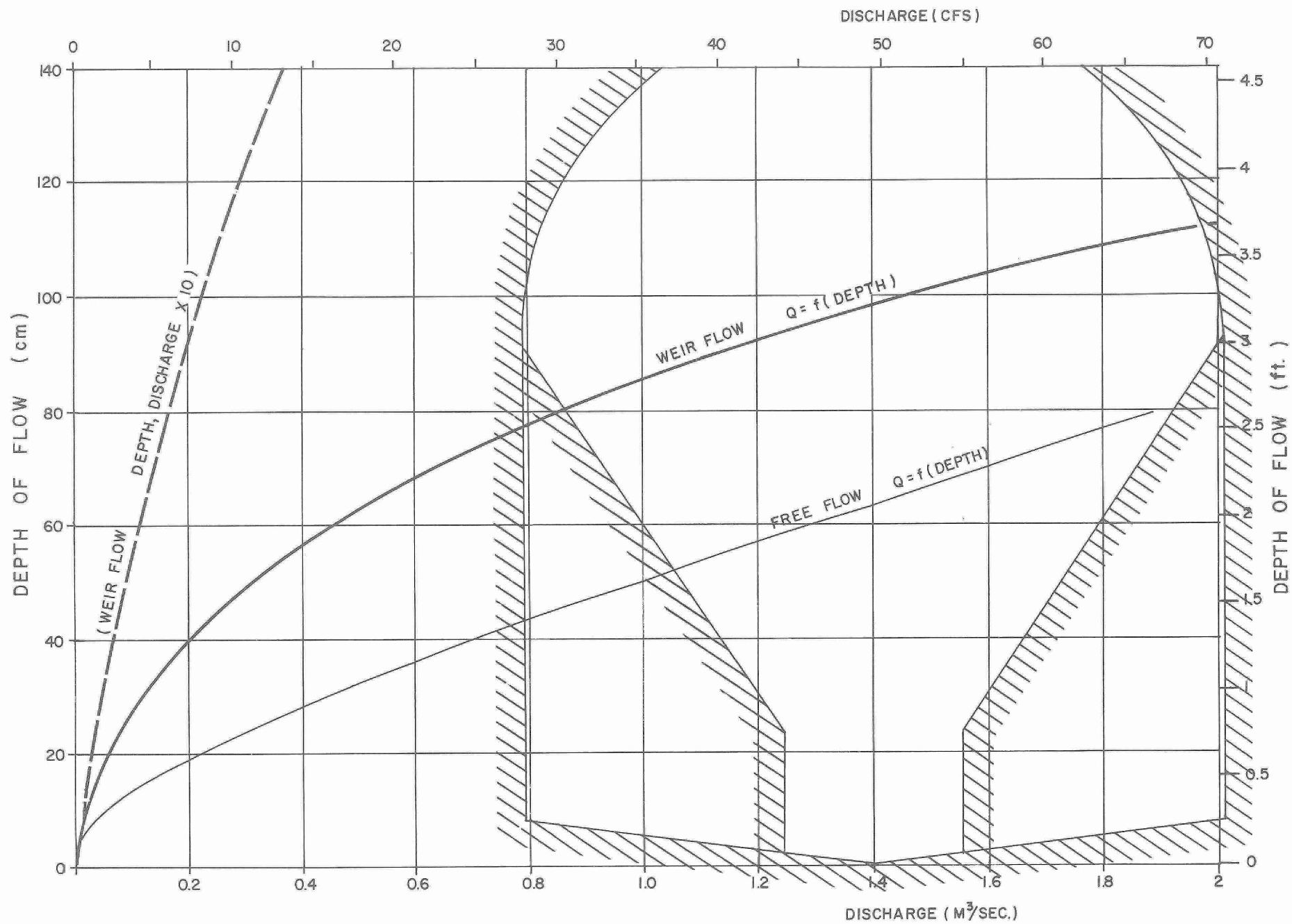


FIGURE 6. WEIR RATING CURVE

signal which is then recorded. A small compressor located in the garage supplied air at a constant rate to the measuring system through an air hose running down into the manhole together with the electrical cables.

The recorder was equipped with a function generator module to automatically convert the depth signal into flow values to facilitate the analysis of data. However, this unit was not very useful because of several inherent limitations, such as the loss of accuracy at low flow depths. In such cases, the flow values were manually read from the depth-discharge calibration curve (Figure 6) using the recorded values of flow depth.

The flow measuring system had the following limitations. Due to the geometric shape of the channel and the physical requirements of the bubbler system, the sensing pipe could not be lowered more than 9 cm (3.5 inches) above the invert, the corresponding flow being $0.02 \text{ m}^3/\text{s}$ (0.7 cfs), which limited the measurement of very low flows. The upper limit of the recording range was set to about $1.3 \text{ m}^3/\text{s}$ (46 cfs) for a 100 percent reading to maintain a reasonable resolution at low flows. Although this was found beneficial for most of the work, the records of flow hydrographs were truncated for about three major storms.

The weir was designed to minimize its influence on dry weather flow, yet an increase of sedimentation was observed upstream of the weir. This factor should be kept in mind when interpreting the pollutant loads.

3.5 Runoff Quality Sampling

Samples of the sewage flow during storm runoff were taken at preset intervals from an intake close to the invert of the sewer, upstream of the measuring weir. The automatic sampler, which was located in the manhole (Figure 3), was activated by the sewage level and collected 24 samples once the trigger signal had turned the unit on.

The sampler operated with a vacuum-compressor pump which drew the liquid into a metering chamber from which any excess volume was purged, and the liquid was drained into one of the 24 sample bottles. The sample lift in this application was 6.7 m (22 ft). The observed time to fill the one-litre metering chamber was approximately 15 seconds, resulting in an average intake velocity of 1 m/s (3.3 ft/s) which is considered very reasonable for such a high sample lift.

A signal was transmitted to one of the chart recorders each time a sample was collected so that sampling events were synchronized and identified with the corresponding flow events to facilitate correlation of the results. The sampler had a special feature to flush the intake tubing and purge the samples and re-start the sampling cycle if the intake tubing was clogged during a sampling event. The intake tubing could convey solid particles up to a maximum diameter of 9.5 mm (3/8 inches).

The samples were removed after the runoff event and delivered to the Water Quality Laboratory of the Canada Centre for Inland Waters, Burlington, where they were preserved and analyzed. In the event the samples were not collected within a reasonable time, particularly during warm weather, analyses were not conducted for non-conservative quality parameters such as BOD.

Sample analysis was carried out for the following parameters:

Solids:

- suspended solids at 105°C
- suspended solids at 550°C

Oxygen demand:

- biochemical oxygen demand (BOD)
- chemical oxygen demand (COD)

Nutrients:

- ammonia (NH_3)
- nitrates and nitrites ($\text{NO}_3 + \text{NO}_2$)
- phosphorus (P)

Metals:

- barium (Ba)
- cadmium (Cd)
- chromium (Cr)
- copper (Cu)
- lead (Pb)
- nickel (Ni)
- zinc (Zn)

All of the above constituents were not analyzed in most of the samples taken. For the SWMM verification, BOD, COD and SS, as well as some of the nutrients, were considered to be most important.

To obtain the dry weather base flow quantity and quality parameters, a separate dry weather program was carried out. This is described separately later in this report.

4 DESCRIPTION OF SWMM AND INPUT DATA REQUIREMENTS

4.1 General

The Storm Water Management Model (SWMM) is a comprehensive mathematical computer simulation program specifically designed to model runoff quantity and quality during the urban rainfall-runoff process. By accurate mathematical representation of the physical system, consisting of the urban watershed and its drainage relief system, its hydrologic and hydraulic response to a given storm event can be generated in terms of outflow hydrographs for the flow and pollutographs for the modelled pollutants.

Subsequent to its initial release in 1970 by the United States Environmental Protection Agency (U.S. EPA), a number of modified versions were released. A brief description of the version used in this study is given below.

4.2 Description of the Program Version

The program version used is referred to as U.S. EPA Release II, September 1970, updated March 1976 by the University of Florida. The model used is described in detail in the U.S. EPA's SWMM User's Manual, Version II [1], in Canadian publications on the SWMM [2], and in a comparative report describing the model's performance in relation to other programs [3]. Further publications describe corrections and improvements to the initial version of the program with partly modified or additional input requirements [4,5]. The program also contains a number of modifications developed by Gore and Storrie Limited in the quality routing section of the RUNOFF block. Some of these are described in a recent document from the University of Florida [5]. These changes should not have affected quantity simulation or quality modelling in the Hamilton Sewer system, which is generally free of surcharge conditions and any of the major flow transitions to which the modifications are applicable.

The main purpose of the phase of the study dealing with the model was to test the RUNOFF and the TRANSPORT blocks of the program for runoff-generating single-event storms by comparing observed and simulated flow hydrographs and pollutographs.

4.3 Runoff Quantity Modelling

Hydrologic response is modelled in the SWMM by the RUNOFF block; the hydraulic response can be simulated either by the RUNOFF block routing routine only or by the more sophisticated TRANSPORT block in conjunction with the RUNOFF block. In the present study, both routing options were tested.

The model input parameters were as given in the SWMM user's manual Version II [1]. The required physical data were extracted from "as built" plans and contour maps supplied by the City of Hamilton and verified during field inspections for accuracy.

4.3.1 Discretization of the watershed

The relatively small size (71 ha or 176 ac) of the test catchment facilitated detailed modelling of the different land uses, surface slopes and pipes with different grades. Thus, the study area was discretized into 78 subcatchments ranging in size from 0.12 ha (0.30 acres) to 4.36 ha (10.77 acres) for the RUNOFF block*. All imperviousness coefficients were computed individually, accounting for different land uses, road patterns and lot depths as determined from the details in the plans and verified by field investigations.

All the sewer conveyance elements of the test catchment were modelled as part of the input data. For the RUNOFF block only, the input data included 72 gutters and pipes. The trunk tunnel was modelled as a rectangular channel four feet wide.

For the simulations with both the RUNOFF and the TRANSPORT blocks, the major elements of the sewer system were taken out of the RUNOFF block to be modelled in the TRANSPORT block. Only 44 gutters and pipes were modelled in the RUNOFF block for this combined simulation, with 28 connection points (inlets) to the TRANSPORT block. The allocation of the different conduits to the two simulation blocks is shown in Figures 7 and 8, schematics of gutter and pipe system as modelled.

* Sub-area schematics are available from the Scientific Authority at the address given at the end of Section 1.

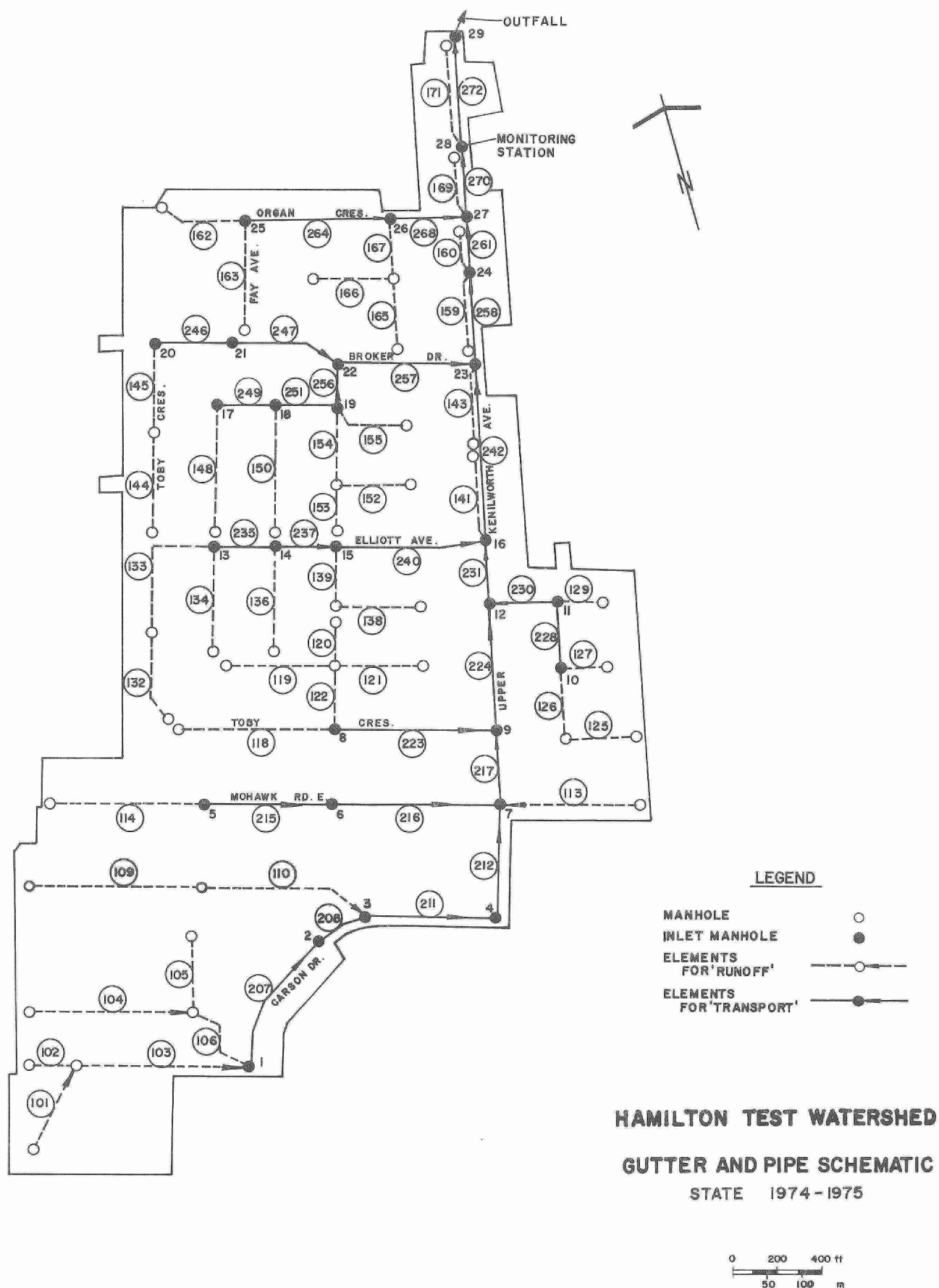


FIGURE 7. GUTTER AND PIPE SCHEMATIC FOR THE TEST CATCHMENT (1974 - 75)

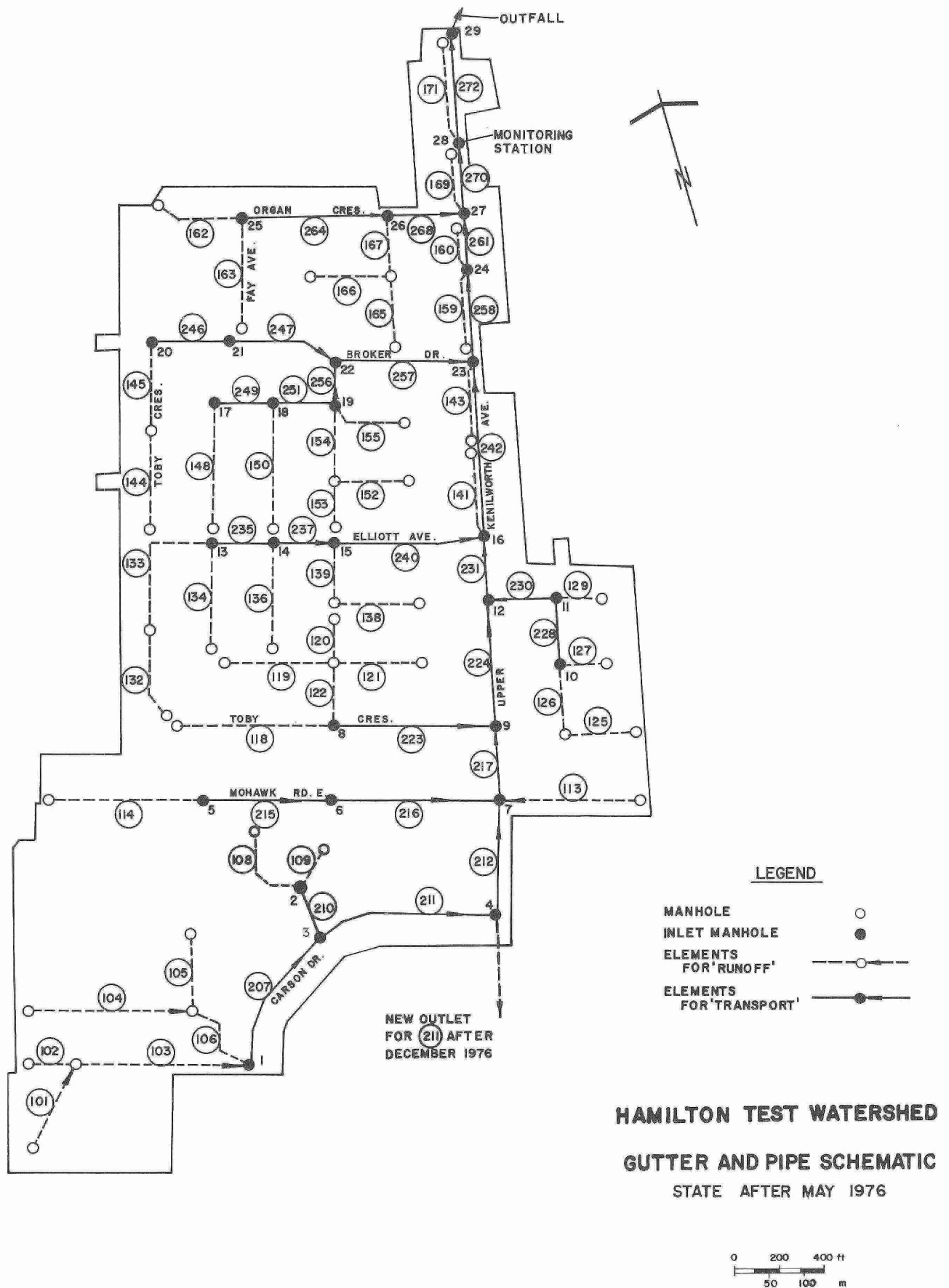


FIGURE 8. GUTTER AND PIPE SCHEMATIC FOR THE TEST CATCHMENT (after May 1976).

The two input data sets for RUNOFF and for the combined simulation with the TRANSPORT block are given in Appendix D*.

The connection between the surface, gutter and pipe flow simulation in RUNOFF and the trunk system simulation in TRANSPORT was provided by 28 inlets. Manhole no. 29 (Figures 7 and 8) is the outfall point of the system which corresponds to the field monitoring station described earlier.

The element data set for the TRANSPORT block is shown in Appendix E*, consisting of 29 manholes and 28 conduits. The trunk tunnel is represented as a rectangular channel with a triangular bottom. The depth of the conduit was adjusted to give the same full cross-section as the original channel profile. Appendix E also shows the linkages and the order of computation.

4.3.2 Input data for other parameters

In order to use rainfall records from the two rain gauges (local and remote as mentioned in Section 3), the watershed was separated into two areas using the perpendicular bisector of a straight line joining the two gauges (similar to the Thiessen polygon method) as the dividing line.

The program default values for infiltration rates and surface storage were modified for a few subcatchments where it was felt appropriate, such as for road surfaces and for vacant lands or open space. For the rest, the default values were used during the initial simulations.

The surface flow resistance factors were also left at model default values in the absence of any better information, except for the subcatchments describing pervious pavement and open space with dense vegetation.

For the impervious areas, the model assumes a constant proportion of the area to be generating immediate runoff which, for all of the watershed, is assigned the default value of 25%. Runoff from the remainder of the impervious area is delayed to account for specified surface storage. For the initial runs, the default values of the program for surface storage and zero detention were assumed.

* Available from the Scientific Authority at the address given at the end of Section 1.

4.4 Runoff Quality Modelling

During runoff-generating storm events, the pollutant loadings from urban areas are drained into the sewer system as parts of the dust and dirt accumulated on the surface. The land uses and antecedent conditions, such as street sweeping practices and length of intervening dry weather periods, largely determine the magnitude of these loadings. Apart from this surface washoff, resuspension of pollutants accumulated in catch basins and deposited in the sewer system are the other two important sources of pollutant loadings during such storm events.

In the SWMM program, the modelling technique initially estimates the dust and dirt load based on the land use details and the antecedent dry weather and street cleaning data; then it expresses the modelled pollutants as fractions of this dust and dirt load, which are then combined with the runoff hydrograph to obtain pollutographs. Details of this approach are given in the SWMM user's manual [1]. The present version of the program can model the following eight pollution parameters:

suspended solids (SS)	settleable solids
BOD	total nitrogen (N)
COD	phosphate (PO ₄)
total coliforms	grease and oil

An option is available to model additional SS due to erosion, if necessary.

The RUNOFF block and the TRANSPORT block can be used separately for quality modelling by providing further data in addition to the basic land use data already provided for runoff quantity simulation and flow hydrograph generation.

The RUNOFF block is designed to simulate surface pollutant loads and catch basin loads and needs the following additional data:

- sub-catchment data such as land use types, catch basin density, total curb length and erosion data if modelled;
- general quality data such as catch basin volume and BOD concentration of content, antecedent dry days and street maintenance data.

The TRANSPORT block, in addition to the above surface and catch basin loads, can model dry weather flow quality loads in combined sewer systems such as the present case, and loads due to resuspension of sediment deposits in the sewer system. The sub-areas used for this block need not be the same as for the RUNOFF block. The additional data required is as follows:

- daily and hourly variation factors for flow and pollutants;
- sub-area data including land use, population densities and income structure;
- flow data for storm event;
- dry weather flow data.

Details of the land use, curb lengths and number of catch basins in this study area were obtained both from plans and in the field. The data for antecedent dry days were based on field investigations. Erosion was not modelled and the method of calculating suspended solids was the same as for the other pollutants. The street sweeping frequency was once a month for residential streets.

4.4.1 Dry weather flow data

The dry weather flow input data for the TRANSPORT block was based on the results of the dry weather flow monitoring program. Twenty-eight sub-areas were modelled, corresponding to the inlets. The dry weather flow and pollutant inputs were the values actually measured and averaged. The program, during simulations, adjusts the internally generated values to produce a total flow equal to the measured dry weather flow.

Infiltration was not modelled, although the dry weather flow quantities indicated a certain amount of extraneous inflow. The model computes the BOD and SS concentrations from observed mass loads. This provides a constant dry weather flow pollutant mass load regardless of the degree of dilution by infiltration.

4.4.2 Dust, dirt and pollutant loading data

In the original version of the SWMM, the pollutant inputs per unit of curb length were developed in an APWA study in Chicago [1]. The dust and dirt loadings assumed in the model per unit curb length are

presented in Table 1. Table 2 gives the amount of pollutants associated with dust and dirt for each land use. These default values were used in this study as no other data were available. In the latest versions of SWMM, the loading rates can be input on an area basis, which is better suited, especially for industrial and commercial areas.

4.4.3 Antecedent dry days

With the dust and dirt accumulation dependent on the number of dry days prior to the storm, as well as the street cleaning interval and efficiency, these values become very important in the development of the initial pollutant loads. The number of dry days includes all days preceding a given storm in which the accumulated rainfall is less than 1.0 inch [1]. This is, of course, a general definition which neglects the variable nature of antecedent storms and their wash-off characteristics, both on the surface as well as in the sewer itself.

In addition, the number of dry days preceding a storm controls the amount of dry weather sediment deposits in the sewer system which is simulated in the TRANSPORT block. The number of dry days has to be specified independently in each block.

The number of dry days must be considered a major calibration parameter for quality modelling for both the RUNOFF and TRANSPORT blocks, although the user's manual discourages variation of this value [1].

4.4.4 Catch basin data

The assumptions for catch basin volumes and BOD content were not verified in the field for this study. The user's manual [1] indicates that the two values should have little effect on the runoff quality.

The general approach used to test the SWMM in this study was based on the assumption that an initial comparison of simulations, using default values (or reasonable variations of these values) for those parameters without specific site data, should show some similarities to the observations in terms of the trends (variation with time) of the hydrographs and pollutographs. In addition, the resulting values for the same variables should be within the same order of magnitude. From such initial results, a detailed calibration procedure would be carried out to

TABLE 1. DUST AND DIRT ACCUMULATION FOR DIFFERENT LAND USES [1]

Type	Land Use	kg DD/dry day/ 100 m - curb	lb DD/dry day/ 100 ft - curb
1	Single-family residential	1.05	0.7
2	Multi-family residential	3.4	2.3
3	Commercial	4.9	3.3
4	Industrial	6.85	4.6
5	Undeveloped or park	2.2	1.5

TABLE 2. MILLIGRAMS OF POLLUTANT PER GRAM OF DUST AND DIRT FOR DIFFERENT LAND USES [1]

Parameter	Land Use Type				
	1	2	3	4	5*
SS	1000.0	1000.0	1000.0	1000.0	1000.0
BOD	5.0	3.6	7.7	3.0	5.0
COD	40.0	40.0	39.0	40.0	20.0
Coliforms**	1.3×10^6	2.7×10^6	1.7×10^6	1.0×10^6	0.0
Settleable solids	100.0	100.0	100.0	100.0	100.0
N	0.48	0.61	0.41	0.43	0.05
PO ₄	0.05	0.05	0.07	0.03	0.01
Grease***	1.00	1.00	1.00	1.00	1.00

* Values for undeveloped and park lands are assumed.

** Units for coliforms are MPN/gram.

***All values are assumed.

improve the model predictions. If, however, for reasonable variations in the values of these parameters (in conformity with the field conditions), the simulated results were to differ very significantly from observed patterns, then the calibration exercise would require further research into the modelling procedures and the representation of the physical processes involved.

5.1 General

In essence, the entire data monitoring and acquisition system operated automatically; power was obtained through the electrical connections to the house where the recording system was housed. The field activities involved were: collecting samples and replacing sample bottles after each event; collecting the recorder charts and replacing them every two weeks; and attending to the other operating and maintenance requirements of the system such as replacing pens, keeping the weir clear of any debris, flushing the sampler intake tubing, etc. The progress of construction activity in the new residential development within the study area was also monitored.

The samples were collected with the least possible delay after each event and then delivered to the laboratory for analysis. The chart records were studied after collection and all important rainfall and runoff events identified, labelled and filed for analysis.

5.2 Dry Weather Flow Data Analysis

As the study area was served by a combined sewer system the sanitary flows constituted a major portion of the dry weather flow. The quantity and quality characteristics of this flow were monitored, so that they could be accounted for in the analysis of storm runoff events.

Dry weather flow monitoring was conducted during two distinct periods, as follows:

- a) Late Fall 1976: a non-continuous recording period (interruptions caused by intervening rains and instrumentation difficulties), covering one week: Monday - Thursday, September 13-16; Saturday - Monday, October 2-4; Thursday - Saturday, November 19-21.
- b) End of Winter 1977/78: a continuous four-day recording period (after the disconnection of the southwestern segment of the watershed) from Tuesday, February 28, 1978, to Friday, March 3, 1978.

Detailed results of laboratory analyses and observed flows are tabulated in Appendix K*. The pertinent results are discussed in summary form in the following few paragraphs.

5.2.1 Dry weather flow rate

To minimize the effect of daily changes in the sanitary flow when calculating the average dry weather flow rates, a consecutive seven-day dry weather flow record would have been desirable. However, as mentioned earlier, the best available record for flow was the discontinuous 1976 record which gave an average seven-day flow of 16.0 L/s. The 1978 record was not considered for this flow averaging process since it was evident that extraneous flows due to infiltration of snow melt had considerably increased the dry weather flows to over 30 L/s.

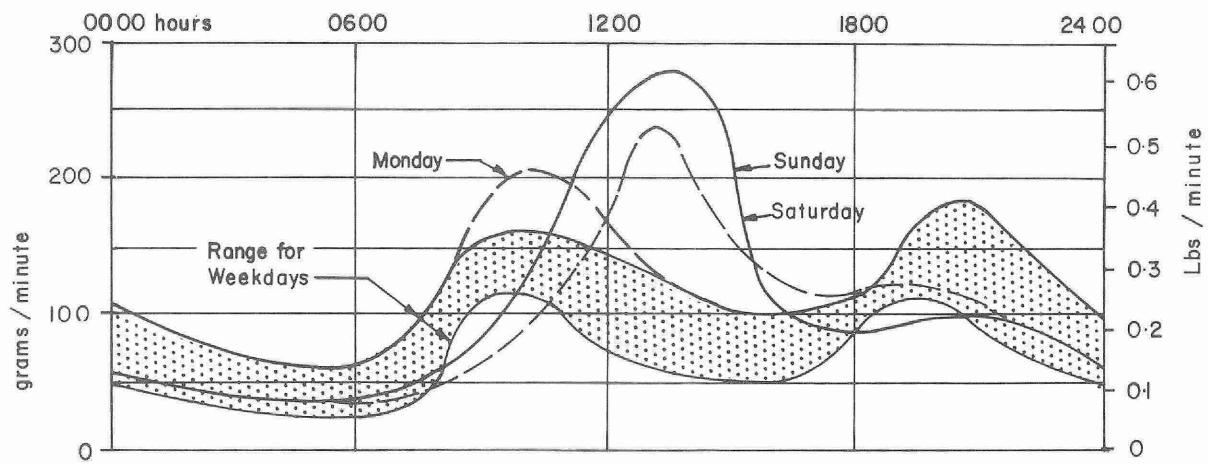
The hourly variations of flows for different days of the week expressed as fractions of the seven-day average flow were used as input data for SWMM quality simulations during modelling, i.e., all the required hourly dry weather flow rates were normalized with respect to the seven-day average dry weather flow for SWMM simulations.

5.2.2 Dry weather pollutant loadings

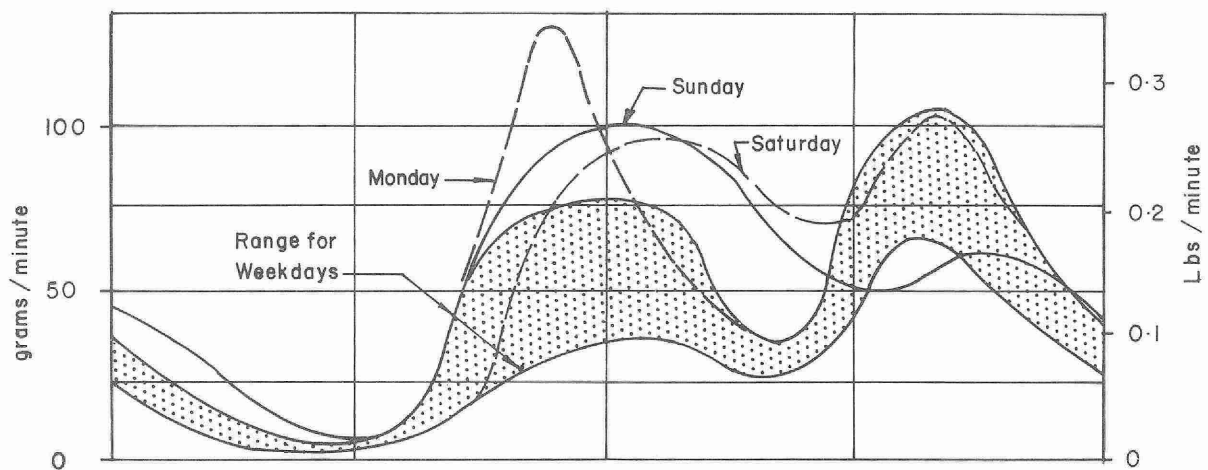
Using the dry weather flow data, the loadings of some of the pollutants were computed on the assumption that the concentrations varied linearly between two consecutive samples. Since the contributing areas (and, therefore, the populations) were different for the two sampling periods, the results are presented separately.

First sampling period (fall of 1976). These samples were collected using the automatic sampling system as installed for this study. The observed hourly variation of flow, BOD and SS for different days of the week are illustrated in Figure 9. The flow is expressed as a percentage of the seven-day average flow of 16.0 L/s and the mass loadings expressed as g/min (lb/min) for the BOD and SS. The variation in week-day pollutant values is shaded as a band since the sampling was limited to only one set of data. The dry weather loadings for the week are summarized in Table 3

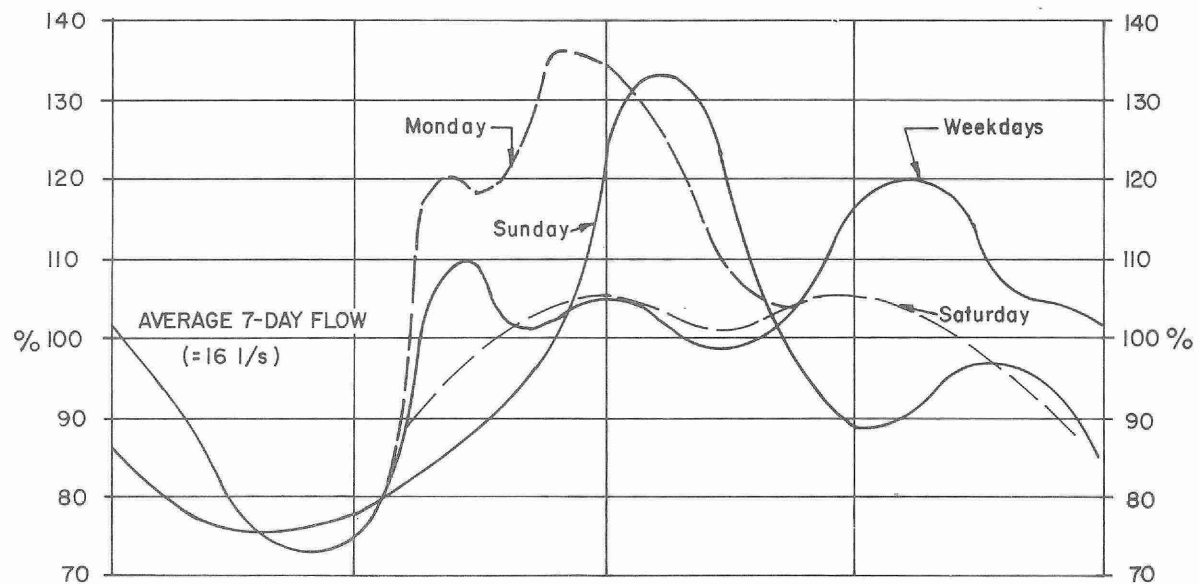
* Available from the Scientific Authority at the address given at the end of Section 1.



(I) TOTAL SUSPENDED SOLIDS MASS LOADINGS



(II) BOD MASS LOADINGS



(III) NORMALIZED DRY WEATHER FLOW

FIGURE 9. DRY WEATHER FLOW AND POLLUTANT MASS LOADING RATES, VARIATION WITH TIME (1976 Data)

TABLE 3. SUMMARY OF DRY WEATHER FLOW POLLUTANT LOADINGS (Fall, 1976)

Description	C O N S T I T U E N T					
	Unit	TOTSS	BOD	COD	N(NH ₃)	P
<u>Concentration:</u>						
Maximum	mg/L	404	213	545	40	10
<u>Mass Loading Rate:</u>						
Average	g/min	100	46	133	13	4
Maximum	g/min	275	217	465	34	10
<u>Per Person Daily Mass Loading Rate:</u>						
Average	g/person/d	47	22	63	6	1.8
Maximum	g/person/d	130	102	220	16	5
Normal Design Values*	g/person/d	90	75			2.3 - 3.9

*Reference [6].

for the constituents BOD, SS, COD, nitrogen (NH₃) and phosphorus (total). The per-person values are based on a population of 3050 for this sampling period.

Comparing the observed concentrations of the pollutants with typical values for untreated sewage (Table 3), it is seen that the average values as observed were generally less than half of the typical values. For the population of 3050 persons in this area, using the normal design assumption of 273 L/person/d (60 Imp.gallons/capita/day), the average DWF would be about 10 L/s. It appears that dilution due to extraneous flows is one reason for the lower-than-average concentrations observed in this study. On the other hand, the observed per person mass loading rates (which are independent of the flow rates) for total suspended solids (TOTSS) were about half the commonly used values; the BOD rates were of the order of one-third these values and the phosphorus rates were about 60 percent (Table 3). These low values are not unreasonable for urban developments. However, it should be noted that the monitoring did not

cover a sufficiently long period of time to establish long-term averages as used in design practice. The observed COD values show proportions of about three times the BOD values, which is quite reasonable for combined sewer flows [6].

Second sampling period (end of 1977 Winter, February/March 1978).

The sampling technique used for this monitoring session was manual grab sampling from close to the water surface, at approximately one-hour intervals, during 12 hours of daytime (from 8:00 am to 6:00 pm) for four consecutive days. The flow depth was also measured at each sampling step.

The results of data analysis are contained in detail in Appendix K (in a separate volume)*. Daily mass loadings and concentrations were not estimated since the records covered only 12 hours of daytime. Hourly loadings as observed for the 1978 sampling period are given in Figures 10 and 11. Figure 11 also shows a comparison of 1976 and 1978 data.

The mass loading rates for SS were about equal in the two samples but were significantly higher for BOD in the second set of samples, even though the population was reduced to about 2050 persons due to the changes made in the sewer connection system at the end of 1976. The discrepancy provides support for the view that the earlier mass loading estimates might not have been "typical" for this watershed. Part of the discrepancy and the overall low estimates of pollutant mass loading rates could be attributed to the differences in the sampling techniques (automatic vs manual), sample locations (close to sewer bottom vs at water surface), and sampling seasons (fall and late winter). However, a difficult aspect of quality monitoring is defining the best location for sampling. Since no ideal location has been established in theory or by practice, it is not possible to make meaningful comments on this aspect of the present study.

During data preparation for quality simulations the average concentration of a pollutant can be obtained by using the mass loading rate and the average sewage flow (excluding any infiltration) and applying the following formula:

$$\text{Average concentration (mg/L)} = \frac{\text{mass loading (g/min)}}{\text{average flow (L/s)}} \times \frac{1000}{60}$$

* Available from the Scientific Authority at the address given at the end of Section 1.

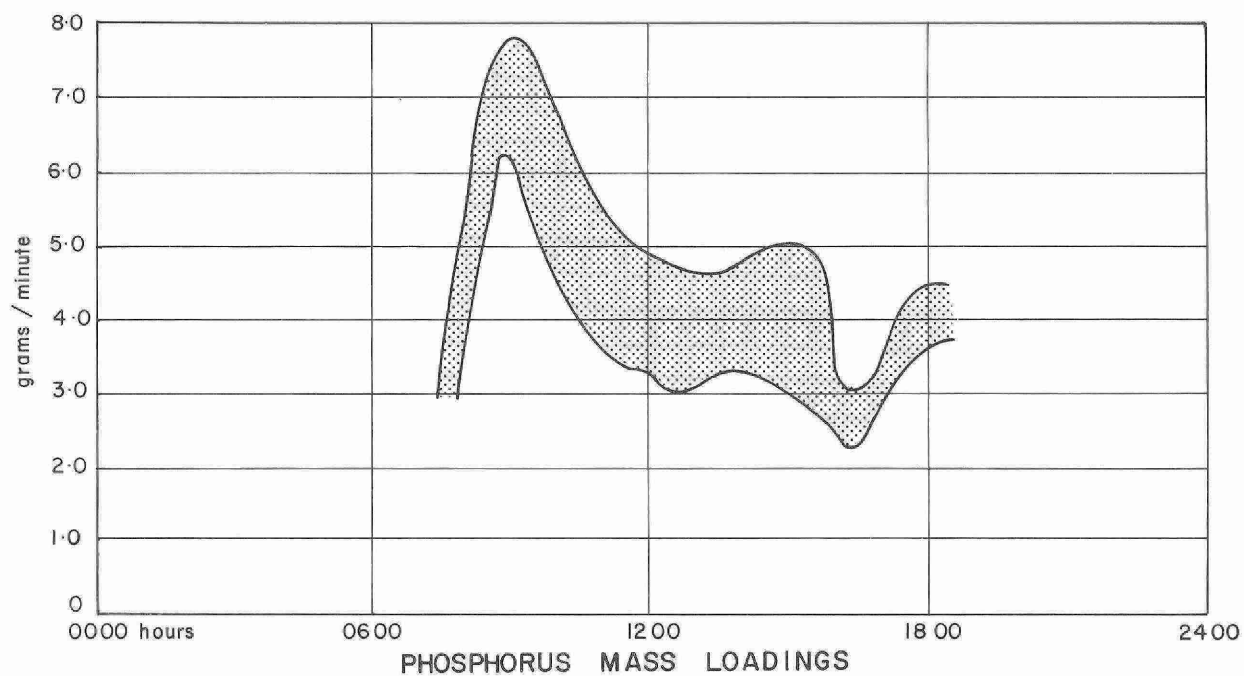
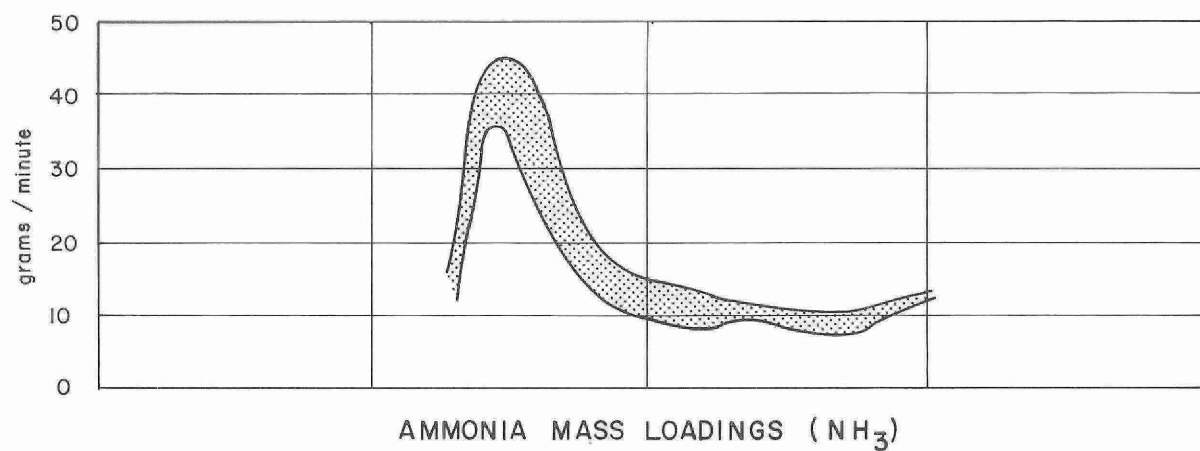
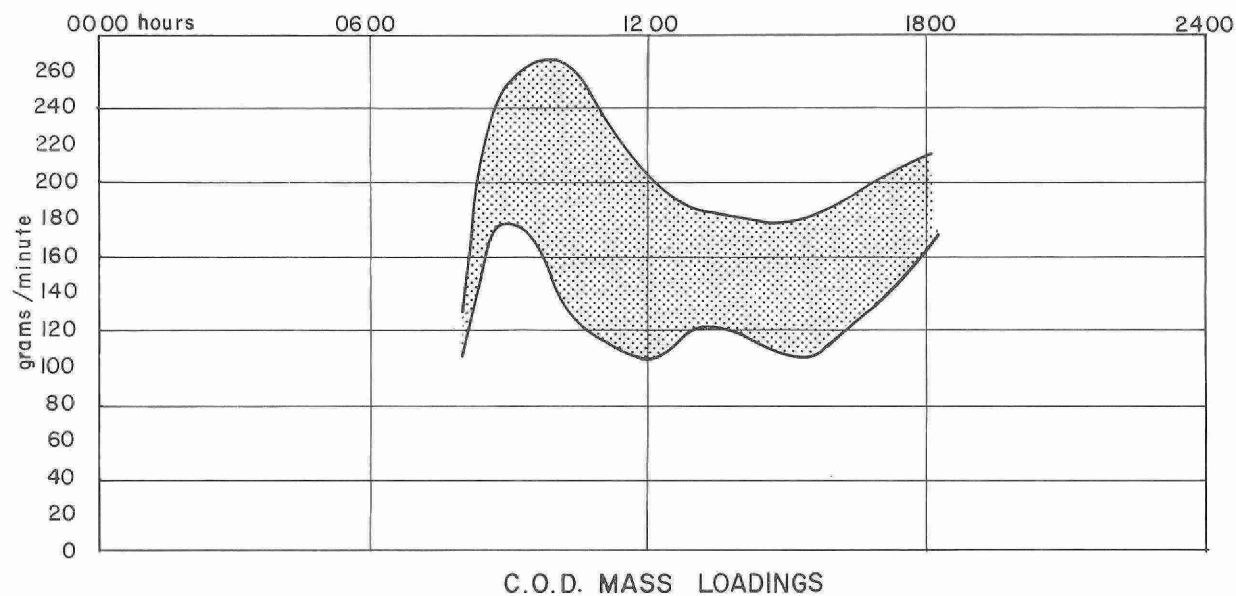


FIGURE 10. RANGES OF POLLUTANT MASS LOADING RATES (1978 Data)

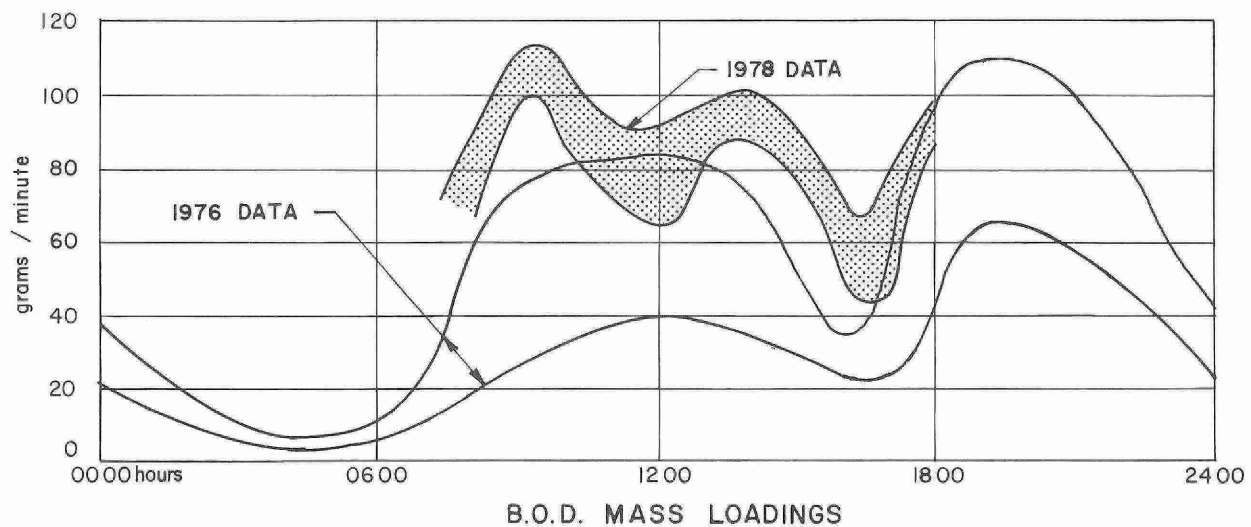
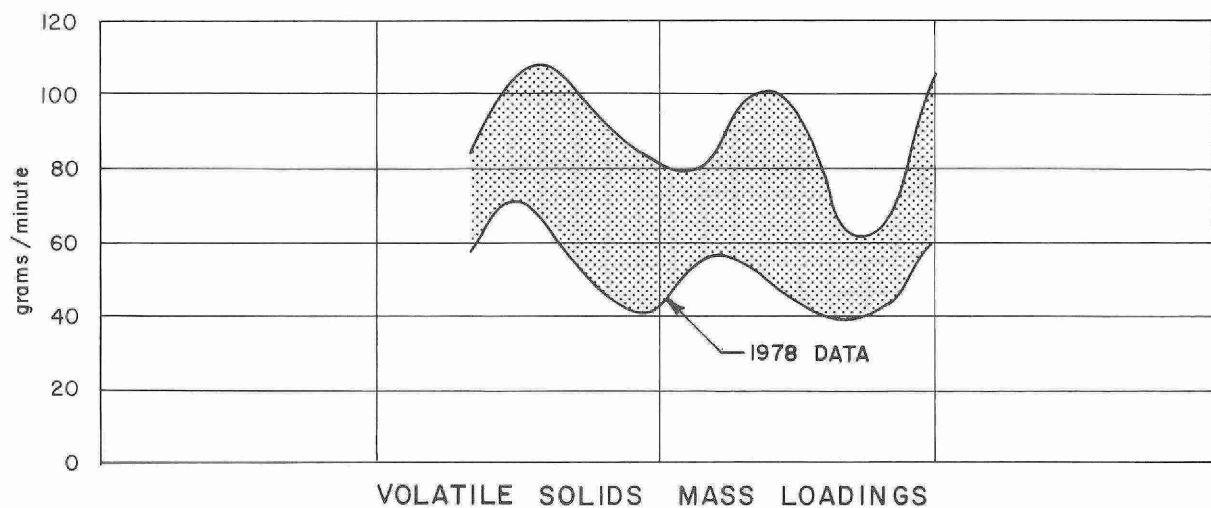
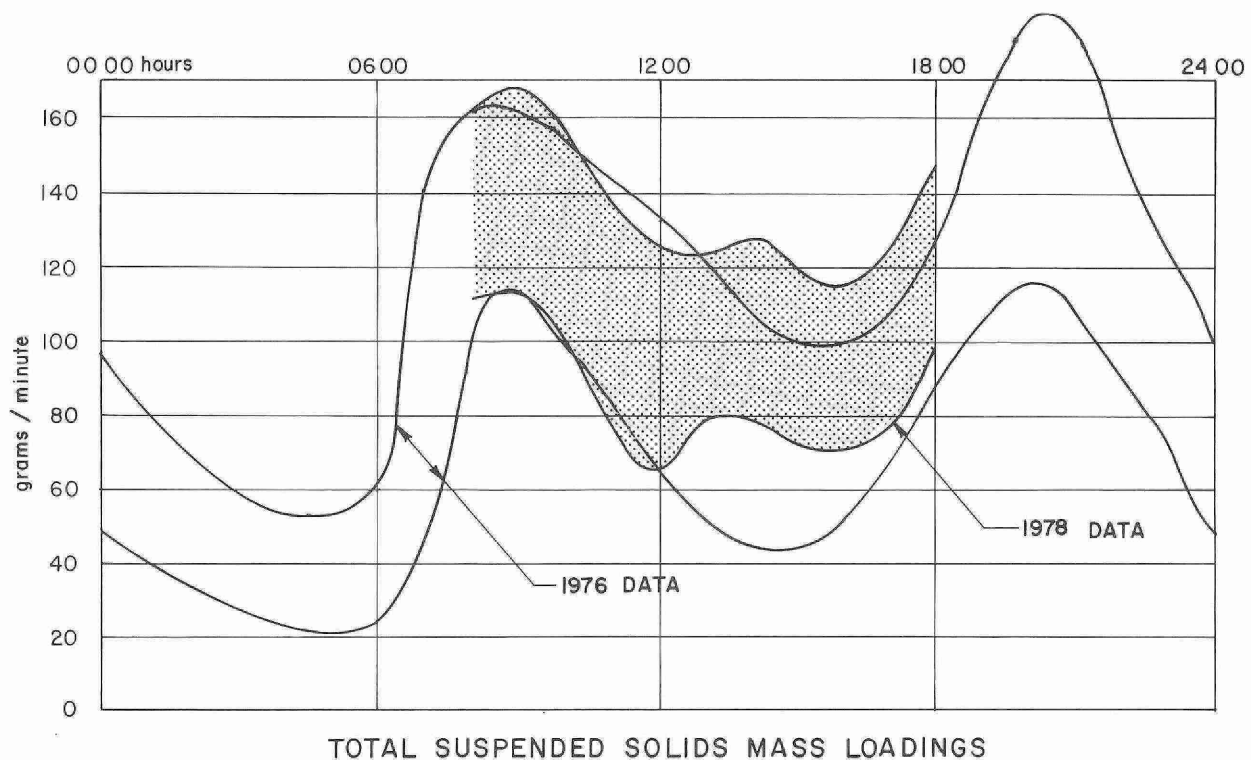


FIGURE 11. RANGES OF POLLUTANT MASS LOADING RATES - COMPARISON OF 1976 AND 1978 DATA

5.3 Wet Weather Flow Data Analysis and Discussion

The monitored data for all storms generating significant runoff were extracted from the strip chart records and catalogued for initial analysis prior to selecting 16 events for runoff simulation. The records were checked to ensure that the rainfall, flow and sampling interval records were adequately synchronized.

Table 4 summarizes rainfall and peak flow data for events up to the end of 1976. A simple comparison of the recorded rainfalls at the two gauges, as shown in Figure 12, shows that the majority of the events were within the range of 0.5 mm to 8 mm of rain. For a reasonable number of these events, the rainfalls recorded were the same at the two gauges. Both records were used to compute rainfall and runoff volumes by allocating a section of the watershed to each of the two gauges as described in Section 4.3.2. Further, the two observed rainfall distribution sets were used as input data during computer modelling with SWMM. Since the recording range of the chart recorder had been adjusted to obtain better resolution for lower flows, the total range covered by the recorder was necessarily limited; the peak runoff rates for certain high intensity rainfalls exceeded the recorder range, as seen in Table 4.

The events as recorded represented a range of rainfalls which could be initially analyzed to study the variation of runoff response with rainfall volume. In general, for low volume rainfalls, the initial abstraction including detention storage and infiltration losses has greater influence on the runoff generation process than for rainfalls with higher volumes and similar antecedent conditions. This effect can be best studied by expressing the runoff volume as a fraction of the total rainfall volume, termed the "volumetric runoff quotient", which is a reliable indicator of cumulative watershed runoff response to any given rainfall volume. It is used in this study only as a general indicator since other assumptions and variables such as uniform rainfall distribution, varying antecedent conditions and different rainfall distributions from event to event, even when rainfall volumes are equal, exert different influences on the value of the estimated volumetric runoff quotient.

TABLE 4. OBSERVED RAINFALL AND PEAK FLOW DATA

Date	Gauge Location				Peak Flow		Remarks
	Local (mm)	(in)	Remote (mm)	(in)	(L/s)	(cfs)	
October 9/75	*	*	1.8	0.07	70	2.5	S
October 9/75	*	*	1.3	0.05	95	3.4	S
November 7/75	2.3	0.09	2.5	0.10	90	3.2	
November 10/75	*	*	17.3	0.68	380	13.4	
November 26/75	5.6	0.22	5.6	0.22	75	2.6	
November 27/75	8.9	0.35	9.9	0.39	120	4.2	S
December 6/75	10.2	0.40	*	*	300	10.6	
December 30/75	*	*	10.2	0.40	53	1.9	S
January 26/76	*	*	24.4	0.96	250	8.8	M
February 15/76	*	*	3.6	0.14	260	9.2	M
February 17-19/76	snowmelt				>500	>18.0	M
February 21-23/76	snow and rain				360	12.7	M
March 4-6/76	instrument malfunction heavy flow (>800 L/s-28 cfs)						M
March 10/76	2.5	0.10	2.5	0.10	115	4.1	
March 12-13/76	7.1	0.28	7.1	0.28	170	6.0	M
	4.3	0.17	4.8	0.19	390	13.8	
March 16/76	2.0	0.08	1.0	0.04	130	4.6	M
March 19/76	*	*	1.3	0.05	175	6.2	M
March 20-21/76	1.0	0.04	1.3	0.05	190	6.7	
	3.3	0.13	3.8	0.15	420	14.8	
	4.3	0.17	5.1	0.20	435	15.4	
March 25/76	7.6	0.30	8.1	0.32	260	9.2	V
March 27/76	*	*	8.9	0.35	925	32.7	
March 31 -							
April 1/76	*	*	29.2	1.15	270	9.5	
April 15/76	1.0	0.04	1.0	0.04	140	4.9	S
April 15-16/76	0.5	0.02	0.5	0.02	60	2.1	
		0.08	2.8	0.11	350	12.4	
April 21/76	1.3	0.05	1.3	0.05	95	3.4	S
April 21-22/76	1.8	0.07	2.3	0.09	165	5.8	
	1.5	0.06	1.5	0.06	85	3.0	
April 22/76	7.6	0.30	8.1	0.32	530	18.7	
April 24/76	6.9	0.27	6.9	0.27	130	4.6	
April 24-26/76	61.7	2.43	67.8	2.67	900	31.8	V
April 26/76	5.3	0.21	5.3	0.21	190	6.7	
May 2-3/76	6.9	0.27	6.6	0.26	260	9.2	
May 6/76	2.3	0.09	2.5	0.10	110	3.9	S
May 6-7/76	55.1	2.17	56.1	2.21	540	19.0	SV
May 11/76	7.4	0.29	7.4	0.29	205	7.2	V
	2.5	0.10	2.5	0.10	330	11.6	
May 16/76	3.0	0.12	3.6	0.14	530	18.7	SV
	7.6	0.30	7.4	0.29	360	12.7	
	6.9	0.27	6.9	0.27	470	16.6	V

TABLE 4. (CONT'D)

Date	Gauge Location				Peak Flow		Remarks
	Local		Remote		(L/s)	(cfs)	
	(mm)	(in)	(mm)	(in)			
June 24-25/76	*	*	27.2	1.07	>1000	>35.0	
June 26/76	3.3	0.13	2.1	0.08	350	12.4	
June 28-29/76	2.8	0.11	2.8	0.11	120	4.2	
	0.5	0.02	0.8	0.03	75	2.6	
	6.4	0.25	7.1	0.28	>800	>28.0	
June 29/76	1.8	0.07	1.0	0.04	120	4.2	S
June 30/76	1.5	0.06	2.3	0.09	210	7.4	
	3.3	0.13	3.6	0.14	455	16.0	
	3.3	0.13	2.8	0.11	210	7.4	
	1.3	0.05	1.3	0.05	150	5.3	
July 1/76	2.0	0.08	2.0	0.08	210	7.4	
	2.5	0.10	2.8	0.11	530	18.7	
	2.8	0.11	2.8	0.11	295	10.4	
	1.3	0.05	2.0	0.08	140	4.9	
	1.5	0.06	1.8	0.07	90	3.2	
July 2/76	0.7	0.03	0.7	0.03	95	3.4	
July 3/76	5.1	0.20	4.8	0.19	135	4.8	
July 10/76	0.7	0.03	0.7	0.03	35	1.2	
July 14-15/76	13.2	0.52	19.3	0.76	>1300	>46.0	SV
July 16/76	2.8	0.11	3.3	0.13	180	6.4	SV
July 20-21/76	0.0	0.00	0.7	0.03	no increase		
July 22/76	1.3	0.05	2.0	0.08	80	2.8	
July 23/76	4.6	0.18	6.6	0.29	905	32.0	SV
July 27/76	6.4	0.25	*	*	340	12.0	S
	7.9	0.31	*	*	420	14.8	
	12.2	0.48	*	*	>1300	>46.0	S
	3.0	0.12	*	*	580	20.5	
July 31/76	6.6	0.26	*	*	>1300	>46.0	
	2.8	0.11	*	*	130	4.6	
	3.0	0.12	*	*	770	27.2	
	0.5	0.02	*	*	95	3.4	
	3.0	0.12	*	*	190	6.7	
August 5/76	0.5	0.02	*	*	32	1.1	
August 7/76	5.3	0.21	*	*	170	6.0	S
August 7-8/76	3.3	0.13	*	*	260	9.2	
August 8-9/76	2.5	0.10	*	*	70	2.5	
	0.7	0.03	*	*	65	2.3	
	2.3	0.09	*	*	80	2.8	
	1.3	0.05	*	*	75	2.6	
August 12/76	2.3	0.09	*	*	300	10.6	S
	1.3	0.05	*	*	255	9.0	
August 13/76	0.5	0.02	*	*	40	1.4	
	1.0	0.04	*	*	50	1.8	
August 14-15/76	10.9	0.43	*	*	1140	40.3	
	1.5	0.06	*	*	125	4.4	
	1.3	0.05	*	*	130	4.6	

TABLE 4. (CONT'D)

Date	Gauge Location				Peak Flow		Remarks
	Local (mm)	(in)	Remote (mm)	(in)	(L/s)	(cfs)	
August 28/76	1.8	0.07	*	*	475	16.8	
September 10/76	2.8	0.11	*	*	145	5.1	
	0.5	0.02	*	*	90	3.2	
September 11/76	3.3	0.13	*	*	130	4.6	
	0.5	0.02	*	*	37	1.3	
September 17/76	1.8	0.07	2.0	0.08	68	2.4	
	1.5	0.06	0.7	0.03	45	1.6	S
	3.0	0.12	3.3	0.13			
	2.8	0.11	3.0	0.12	310	10.9	
	3.6	0.14	3.0	0.12	320	11.3	
September 17-18/76	1.0	0.04	1.0	0.04	270	9.5	
	1.5	0.06	1.3	0.05	120	4.2	V
	2.5	0.10	1.8	0.07	180	6.4	V
	1.8	0.07	2.5	0.10	230	8.1	V
	13.0	0.51	15.0	0.59	600	21.2	V
	3.8	0.15	3.6	0.14	330	11.7	V
September 18/76	2.3	0.09	0.5	0.02	135	4.8	
September 20/76	2.8	0.11	4.1	0.16	250	8.8	
September 21/76	3.0	0.12	3.0	0.12	170	6.0	
September 23/76	3.8	0.15	3.3	0.13	90	3.2	
September 25/76	12.4	0.49	11.7	0.46	155	5.5	
October 6-7/76	2.5	0.10	2.8	0.11	170	6.0	V
	3.6	0.14	4.6	0.18	565	20.0	V
	4.6	0.18	5.1	0.20	540	19.1	V
October 8-9/76	1.0	0.04	1.3	0.05	65	2.3	
	1.0	0.04	1.0	0.04	170	6.0	
	6.9	0.27	8.1	0.32	150	5.3	
October 13/76	0.7	0.03	1.3	0.05	70	2.5	
October 20/76	2.8	0.11	*	*	55	1.9	
	2.0	0.08	*	*	50	1.8	
October 21/76	7.6	0.30	*	*	140	4.9	
October 30-31/76	1.0	0.04	1.0	0.04	45	1.6	
	3.8	0.15		0.14	85	3.0	
	1.8	0.07	3.6	0.07	75	2.6	
	1.3	0.05	1.3	0.05	50	1.8	
November 26/76	3.8	0.15	*	*	110	3.9	
November 27/76	1.8	0.07	*	*	80	2.8	

* - No record

S - Sampled event

M - Snowmelt

V - Event used for verification

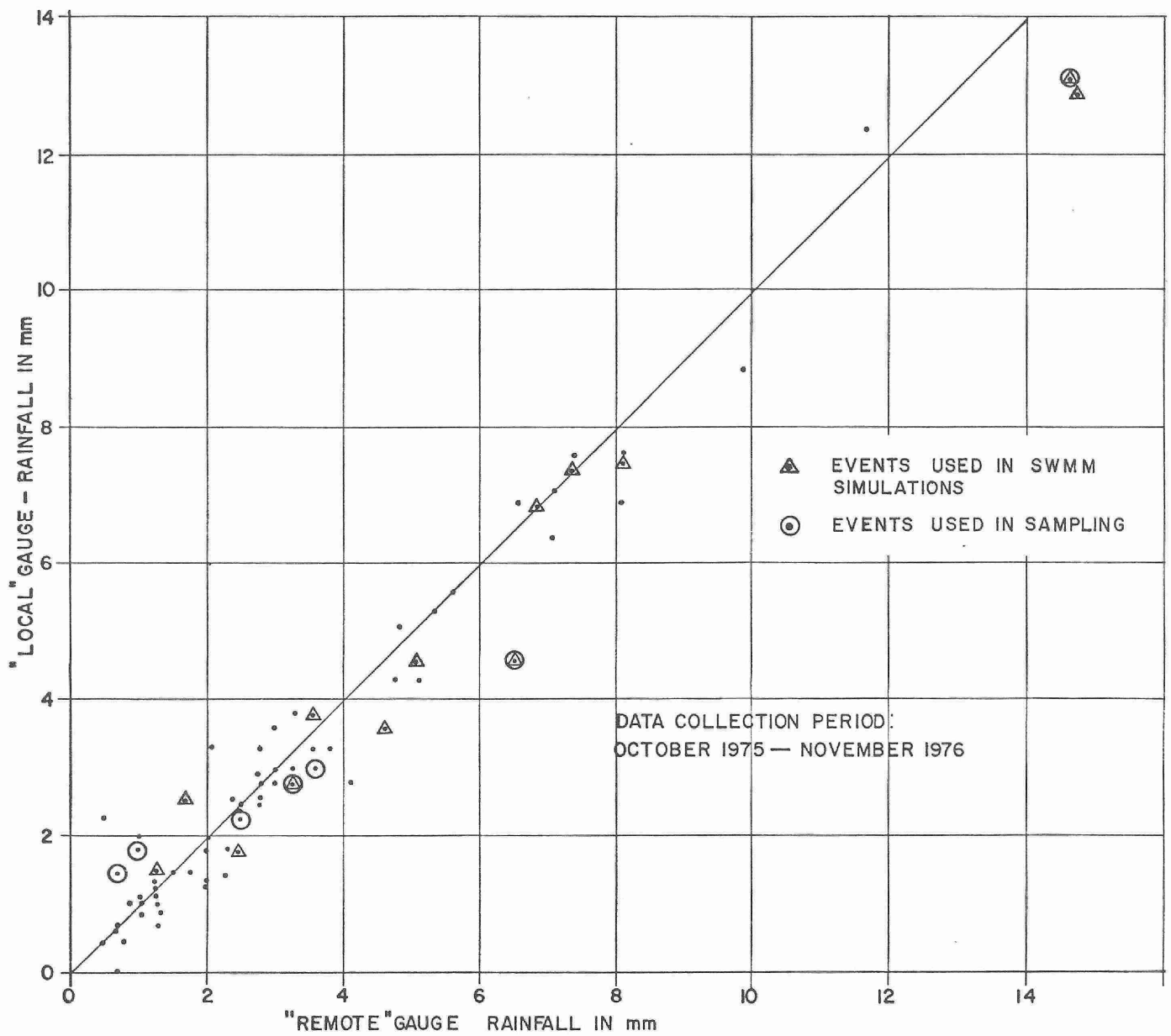


FIGURE 12. COMPARISON OF THE TWO RAIN GAUGE RECORDS

These rainfall and runoff computations were carried out for a number of selected events representing the total range of observed rainfall volumes and durations. For the same events, initial SWMM RUNOFF block simulations were conducted using the modelling techniques described in Section 4, with the default values for infiltration rates, and initial abstraction. These results are summarized in Table 5 for comparison. The rainfall volume assumes uniform aerial distribution of the values recorded at the two gauges and the measured runoff represents the net estimated runoff volume after subtracting the dry weather flow volume from the total flow hydrograph on the basis of prevalent runoff rate preceding the storm.

The preliminary computations showed that the computed volumetric runoff quotient generally increased with the rainfall volume. This computed general increase in the value of runoff quotient with rainfall volume indicates that lesser rainfall events are more sensitive to initial abstraction and the antecedent moisture conditions, as expected. The antecedent moisture conditions and actual rainfall distribution also have significant effects as indicated by the variation of the runoff quotient for different events with equal computed rainfall.

The simulated values of the runoff quotient were consistently higher than the computed values except for events with less than 2 mm rain and for the two events with high volumes of rainfall (66.7 and 56.1 mm). The computed runoff quotients for the above long-duration events were almost twice the values given by simulation. This was prior to modifying the infiltration values as given in Table 5. The higher simulated values for all other rainfall events of greater than 2 mm lead to the suspicion that, for these two events, the extraneous flows experienced were very significant. This could possibly have been due to sewer infiltration induced by the geological structure of the area, which was described in Section 2. Therefore, it was necessary that the default values of infiltration rates used in these initial simulations be re-assessed during calibration of the model. In addition, the higher values of the simulated results for the runoff quotient and the peak flows indicated that some of the areas, such as detention storage, were contributing direct runoff. The values for directly-draining impervious areas were also to be reviewed during the calibration process. These results were used during calibration of the model (Section 6).

TABLE 5. EVENTS SELECTED FOR ANALYSIS AND SIMULATION (with results of initial simulation runs)

Date	Rainfall Volume (m ³)	Measured Runoff (m ³)	Simulated Runoff (m ³)	Runoff Quotient		Peak Flows ^a	
				Measured	Simulated	Measured (L/s)	Simulated (L/s)
March 25/76	5705	1510	1780	0.265	0.312	260	325
April 24/76	47340	39000, 23505 ^e	18500, 22480 ^f	0.82, 0.497 ^e	0.39, 0.475 ^f	900	925
May 6-7/76	39850	25500 14290 ^e	15050	0.64, 0.359 ^e	0.378	540	540
May 11/76 a.m.	5395	1398	1675	0.259	0.310	205	275
May 16/76 a.m. ^b	2390	630	675	0.264	0.282	530	540
May 16/76 p.m.	4895	1340	1495	0.274	0.305	470	525
July 16/76	12630	>3400	7345		0.582	>1300	3500
July 20-21/76 ^b	2275	480	520	0.211	0.229	180	220
July 27/76	4345	1260	1325	0.270	0.305	905	960
September 17-18/76 ^b	26000	8280	9392	0.318	0.365	600	725
October 6-7/76 I	1970	330	420	0.170	0.213	170	220
II	3115	930	1150	0.300	0.370	565	735
III	3580	1075	1315	0.300	0.367	540	670
May 11/76 p.m. ^c	1500	575	240	0.383		305	
July 29/76 ^d	4555	1080	1370	0.237		>1300	
July 31/76 ^d	2195	350	500	0.159		720	
August 7/76 ^d	4200	1060	1230	0.252		155	
August 14/76 ^d	7745	1680	2510	0.217		1100	
July 15/77	1018	186	168	0.183	0.166		
July 19/77 I	1197	270	187	0.226	0.157	190	100
II	2987	810	1064	0.271	1.356	800	935
August 1/77	1776	495	517	0.279	0.292	420	465
August 3-4/77	10111	>2010	4007		0.396	>1300	2250
August 24/77	3107	738	1021	0.237	0.304	135	215
August 5/77 ^d	417	77	36	0.186	0.087	15	
August 8/77 ^d	13204	>3840	5435		0.411	>1300	
August 10/77 ^d	5282	2138	1955	0.405	0.370	595	
August 11/77 ^d	4448	1458	1563	0.328	0.357	220	
August 21/77 ^d	4170	873	1464	0.209	0.351	180	
October 8/77 ^d	4865	1602	1751	0.329	0.360	155	
October 11/77 ^d	834	153	74	0.184	0.088		

^a 1976 peak flows include base flow; 1977 peak flows exclude base flow.

^b also used for pollutant simulation.

^c rejected because of significant antecedent rain influence.

^d rejected; only one rainfall record available.

^e with increased base flows.

^f with modified infiltration.

The watershed response time, as indicated by the interval between an observed peak rainfall intensity and the corresponding peak flow was found to vary significantly from one event to another. To study its variation, the graphical plot shown in Figure 13 was produced using observed rainfall distribution for the remote gauge record and the hydrographs. It appeared that this parameter varied considerably at low peak flows and tended to become constant at larger peak values. For this watershed, as shown in Figure 13, the constant value was about 14-16 minutes. Since high flow rates were normally generated by high intensity rains typical of thunderstorms, and the low peak values occurred for low intensity rains, response times which significantly deviated from the minimum value refer to low intensity and spatially uneven storms. This is an indicative result that needs to be further studied in the future.

The overall simulated hydrograph shapes reproduced the observed pattern of response reasonably well for all events, even though the absolute values and times of occurrence were not reproduced exactly. Therefore, as an initial interpretation of the results, it could be stated that the SWMM RUNOFF block, using the gutter routing option, was capable of modelling the catchment response quite well for events not inducing surcharged flows in the sewers, especially if the physical watershed parameters and the routing system were modelled with reasonable accuracy.

These initial comparisons were used in the final calibration procedure adopted for further improving the simulation results (see Section 6).

5.4 Wet Weather Flow Quality Data Analysis and Discussion

A summary of the rainfall events which were sampled during this study is given in Table 6. The results of the laboratory sample analysis carried out for the parameters mentioned in Section 3, and the corresponding times and the flow values as recorded by the automatic recorders, are given in Appendix G*. The results of the computations carried out to estimate sampled maximum mass loading rate (flux) of constituents such as total suspended solids, BOD, COD, nitrogen and phosphorus are given in Table 7.

*Available from the Scientific Authority at the address given at the end of Section 1.

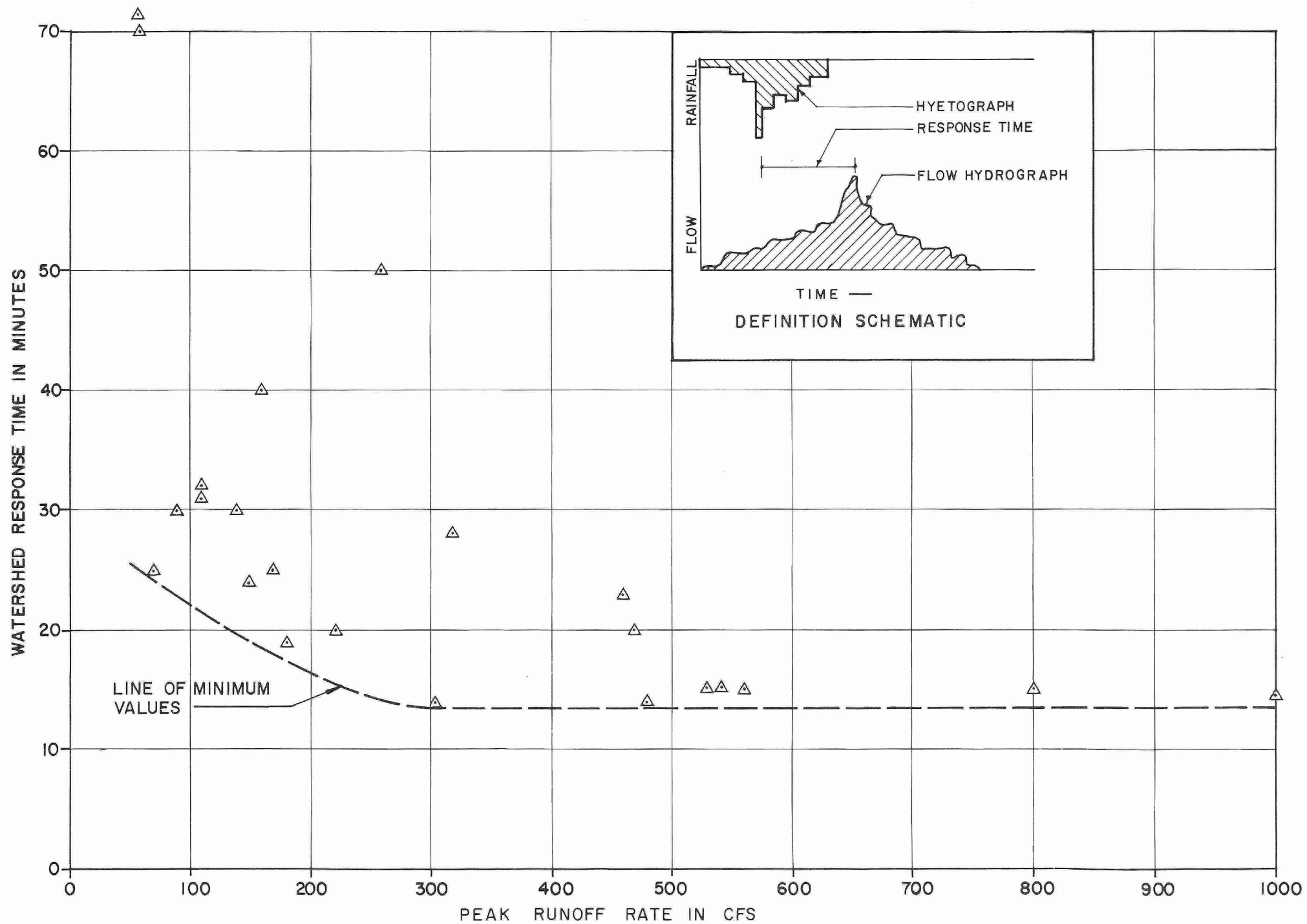


FIGURE 13. VARIATION OF WATERSHED RESPONSE TIME WITH PEAK RUNOFF RATE

TABLE 6. LISTING OF SAMPLED EVENTS

Date	Rainfall (in)	Peak Flow		Number of Samples	Intervals (min)	Time Covered (h)
		(L/s)	(cfs)			
October 9, 1975	0.07	70	2.5	24	6.5	0853 - 1122
October 9, 1975	0.05	94	3.3	12	13.0	1950 - 2213
November 27, 1975	0.39	120	4.2	19	6.9	1050 - 1255
December 30, 1975	0.40	53	1.9	12	13.6	1240 - 1510
April 15, 1976	0.04	140	4.9	12	10.0	0748 - 0938
April 21, 1976	0.04	90	3.2	11	10.0	1255 - 1535
May 6, 1976 I	0.10	110	3.9	12	10.0	0320 - 0420
May 6, 1976 II		225	7.9	12	15.0	1115 - 1400
May 16, 1976	0.14	530	18.7	12	7.5	0425 - 0548
June 29, 1976	0.06	120	4.2	23	7.5	1410 - 1720
July 16, 1976	0.75	>1300	>46.0	24	7.5	0605 - 0900
July 20, 1976	0.13	180	6.4	12	7.5	2305 - 0030
July 27, 1976	0.27	900	31.8	12	7.5	0655 - 0820
July 29, 1976 I	0.25	330	11.7	24	6.5	0130 - 0425
July 29, 1976 II	0.46 + 0.12 + 0.25	>1300	>46.0	24	3.5 - 6.5	1130 - 1350
July 31, 1976	0.10	130	4.6	12	5.6 - 20	0950 - 1220
August 7, 1976	0.23	170	6.0	12	6.5 - 20	1650 - 1925
August 12, 1976	0.10 + 0.05	300 + 250	10.6 + 8.8	17	6.5	1255 - 1530
August 29, 1976	2 hours after peak runoff			24	2.0 - 7.5	
September 17, 1976	0.06 + 0.11 + 0.27	320	11.3	24	5.5	1525 - 1730
July 15, 1977	0.08	150	5.3	20	6.0	2032 - 2229
August 1, 1977	0.12	480	17.0	17	10.0 - 30.0	0212 - 0602
August 3-4, 1977	0.77	460/>1300	16.2/>46.0	18	10.0 - 30.0	2256 - 0246
August 8, 1977 I	0.20	98	3.5	23	10.0	0055 - 0435
August 8, 1977 II	0.95	>1300	>46.0	11	10.0	1325 - 1505
August 24, 1977	0.22	160	5.7	24	10.0	0113 - 0503

TABLE 7. MONITORED MAXIMUM WET WEATHER POLLUTANT LOADING RATES

Date	Preceding Dry Days	Rainfall Data				Maximum TOTSS		Maximum BOD		Maximum COD		Maximum N(NH ₃)		Maximum P	
		Volume	Duration	Maximum	Peak	Concen-	Mass	Concen-	Mass	Concen-	Mass	Concen-	Mass	Concen-	Mass
		(mm)	(min)	Inten- sity (mm/hr)	Runoff Rate (L/s)	tration (mg/L)	Flux (g/min)	tration (mg/L)	Flux (g/min)	tration (mg/L)	Flux (g/min)	tration (mg/L)	Flux (g/min)	tration (mg/L)	Flux (g/min)
Dry Weather Flow	-	-	-	-	16	404	275	213	217	545	465	40	34	10	10
October 9/75 I	-	1.8	90	2.0	70	538	1814	131	527	*	-	*	-	*	-
October 9/75 II	Nil	1.3	50	3.8	95	648	3616	*	-	*	-	*	-	*	-
November 27/75	1/2	9.4	180	1.0	120	236	1650	47	328	*	-	*	-	*	-
December 30/75	24	10.2	189	2.5	53	588	1870	> 50	> 138	*	-	*	-	*	-
April 15/76	14	1.0	< 5	94.0	140	2740	22194	>150	>1215	1970	15957	31	235	26	211
April 21/76	6	1.3	20	2.5	85	784	3857	*	-	1120	5510	18	89	14	69
May 6/76 I	3	2.4	108	3.8	110	728	4455	> 22	> 135	820	5018	12	73	9	55
May 16/76	5	3.3	15	58.4	530	2000	40528	130	3120	475	12540	7	185	7	185
June 29/76	-	1.4	24	12.7	118	145	900	25	170	85	542	11	50	4	28
July 16/76	1	16.3	28	114.0	>1300	1590	124020	21	>1638	207	>16146	*	-	*	-
July 20/76	4	3.1	74	3.8	180	836	9029	145	1566	893	9644	*	-	*	-
July 27/76	3	5.1	36	38.0	900	755	34656	31	1488	655	31440	*	-	*	-
July 29/76 I	2	6.4	97	8.5	330	358	3821	59	425	342	2975	*	-	*	-
July 29/76 II	-	6.6	13	38.0	>1300	1470	>114660	6	> 156	99	> 6006	*	-	*	-
July 31/76	2	2.8	43	15.2	130	142	930	*	-	*	-	*	-	*	-
August 7/76	2	5.3	257	3.8	170	442	3448	*	-	530	4134	7.5	56	5.4	42
August 12/76	3	2.3	4	30.5	300	2180	39240	200	3600	1340	24120	13	234	15	270
September 17/76	6	9.4	>60	30.0	320	2010	37386	150	2790	1410	26266	7.7	191	12.0	115
July 15/77			53	5.2	150	1060	8268	230	1794	1200	9360	10	90	9.0	70
August 1/77	11	2.9	9	32.0	480	2180	62748	*	-	1900	54720	9	259	14.0	403
August 3-4/77	2	17.8	23	20.0	460	-	-	*	-	733	20230	8	152	5.4	150
August 8/77	3	5.13	130	3.5	98	628	1960	120	410	800	2928	11	40	7.8	25
August 24/77	3	5.6	150	5.0	160	194	1397	115	828	340	2448	9.7	32	3.7	26

* not tested for this pollutant.

The following observations were made after a comparative study of the results of laboratory analyses and the corresponding rainfall and flow hydrograph data.

It was observed that for all sampled events, the shape of the pollutograph was much sharper, with rapidly increasing rising limb and rapidly decreasing falling limb, compared to the changes in the flow rates of the corresponding flow hydrograph, clearly indicating a markedly high pollutant load rate at the initial stages of the storm runoff. This is considered supporting data for the existence of a 'first flush' generally experienced in combined sewers during storm runoff events. The tables of values in Appendix G* show that the sampling intervals varied from two minutes to 15 minutes for different events, and that for certain events, some intermediate samples or flow values were missed; thus, any total mass loading estimate on an event basis would be only very approximate. This is further affected by the general absence of samples for the initial sections of the hydrograph, a drawback associated with the turn-on delay inherent to the adopted automatic sampler. Therefore, mass loads of pollutants on runoff volume basis were not estimated.

The observed DWF maximum pollutant concentrations and the maximum mass loading rates are given at the top of Table 7 for comparison with the wet weather values. The wet weather concentrations and mass loading rates expressed as multiples of the maximum dry weather values are as follows:

Observed Range of Maximum Values from Table 7

Pollutant	Concentration Ratio (WWF/DWF)	Mass Loading Rate Ratio (WWF/DWF)
Total SS	0.5 - 6.5	3.3 - 450
BOD	0.03 - 1.1	1.0 - 17
COD	0.18 - 3.6	5.4 - 118
N(NH ₃)	0.18 - 1.0	1.0 - 7.6
P	0.4 - 2.6	2.6 - 27

* Appendices are available from the Scientific Authority at the address given at the end of Section 1.

This shows that, compared to even the maximum dry weather values, the total suspended solids loadings were high. Table 7 shows that the lower range values for all pollutants were associated with storms of smaller rainfalls (<4 mm rain) and with events of fewer antecedent dry days (0 - 2 days); the maximum loadings were associated with high intensity rainfalls such as summer storms, particularly after prolonged dry spells. These figures demonstrate that, in combined sewers, the pollutant loadings concentrations and rates generated by non-point sources on the surface can reach significantly high values, depending on storm conditions.

It is clearly seen that high intensity storms (e.g., April 15, May 16, July 16, 1976, etc.) generated the highest concentrations and loading rates of all pollutants. This can be attributed to the increased flow velocities and the resulting higher pollutant carrying capacity of the flows for such events. These flows pick up and convey enhanced loads from the surface and the resuspended pollutant deposits from the sewers. The effect of antecedent rain is shown by the marked decrease in BOD and COD loading rates with the decrease in the number of preceding dry days (e.g., events of July 16 and July 29 II, 1976).

The durations of higher suspended solids load concentrations appear to be related to the peak flow rates, the antecedent dry days and the rainfall volumes. This can be seen in Table 8 which gives results of some selected events. These results can be treated only as indicative. The very high pollutant load ratings (for BOD, COD, N and P) induced by the short duration high intensity storm of April 15, shown in Table 8, can be attributed to re-suspension since the suspended solid loadings were low, indicating a lower surface contribution for the prolonged antecedent dry period of 14 days.

The total suspended solids (non-filterable) were separated into the volatile and the non-volatile components. The non-volatile component is identified in the pollutographs as suspended solids. It was generally observed that, for most of the events, the volatile component loading was initially much higher than the non-volatile material, indicating possible re-suspension of combined sewer deposits (See Figures 14, 15 and 16). The

TABLE 8. DURATION OF WET WEATHER POLLUTANT LOADINGS EXCEEDING ASSUMED PEAK RATES

Event	Rain (mm)	Maximum Intensity (mm/hr)	Peak Flow	Ante- cedent Dry Days	Duration in Minutes in which Concentrations Exceeded Assumed Values				
					TOTSS >1500 mg/L	BOD >100 mg/L	COD >1000 mg/L	N(NH ₃) >10 mg/L	P >10 mg/L
October 9/75	1.8	2.0	70		-	15	-	-	-
April 15/76	1.0	94.0	140	14	-	>15	>40	>120	>20
April 21/76	1.3	2.5	85	6	-	-	32	> 60	20
May 6/76 I	2.4	3.8	110	3	-	-	-	> 10	-
May 16/76	3.3	58.4	530	5	20	7	-	-	-
July 16/76	16.3	114	1300	1	10	-	-	-	-
July 20/76	3.1	3.8	180	4	-	>15	-	-	-
August 12/76	2.3	30.5	300	3	15	>10	>10	> 10	>10
September 17/76	9.4	30	320	6	13	20	5	-	11

MAXIMUM OBSERVED DRY WEATHER CONCENTRATIONS

Pollutant	Max. Concentration (mg/L)
TOTSS	404
BOD	213
COD	545
N(NH ₃)	44
P	10

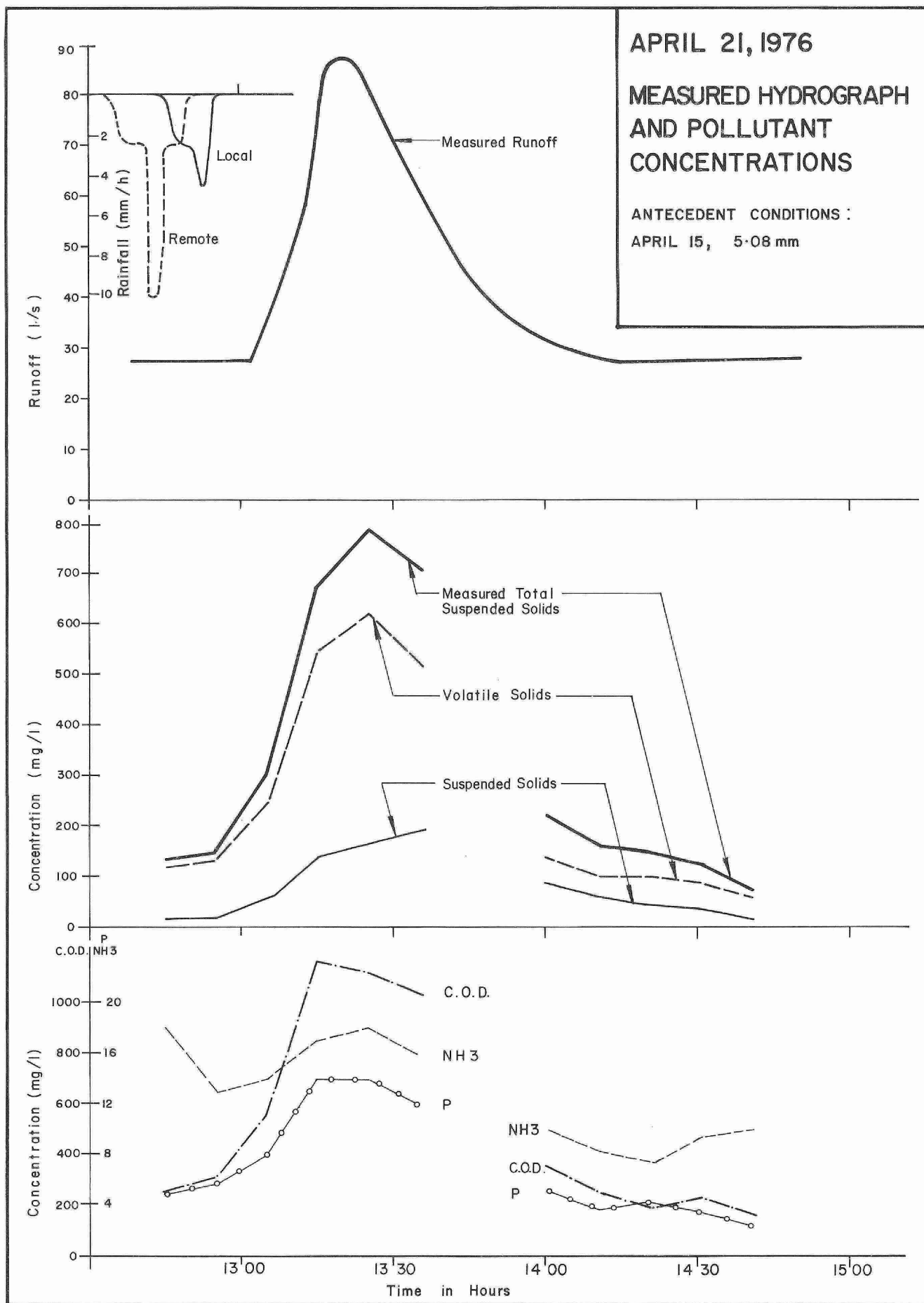


FIGURE 14. MEASURED HYDROGRAPH AND POLLUTANT CONCENTRATIONS, APRIL 21, 1976

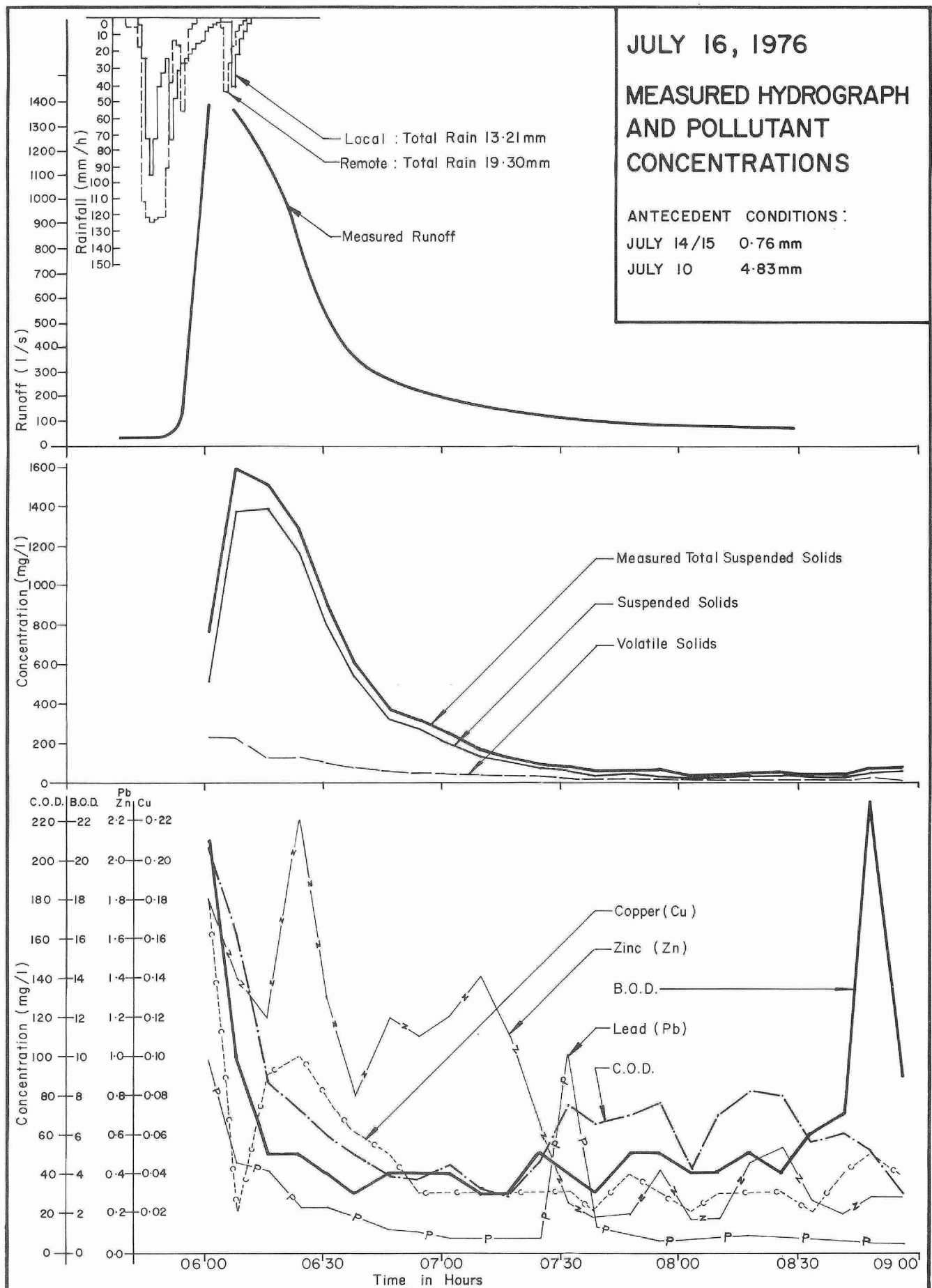


FIGURE 15. MEASURED HYDROGRAPH AND POLLUTANT CONCENTRATIONS, JULY 16, 1976

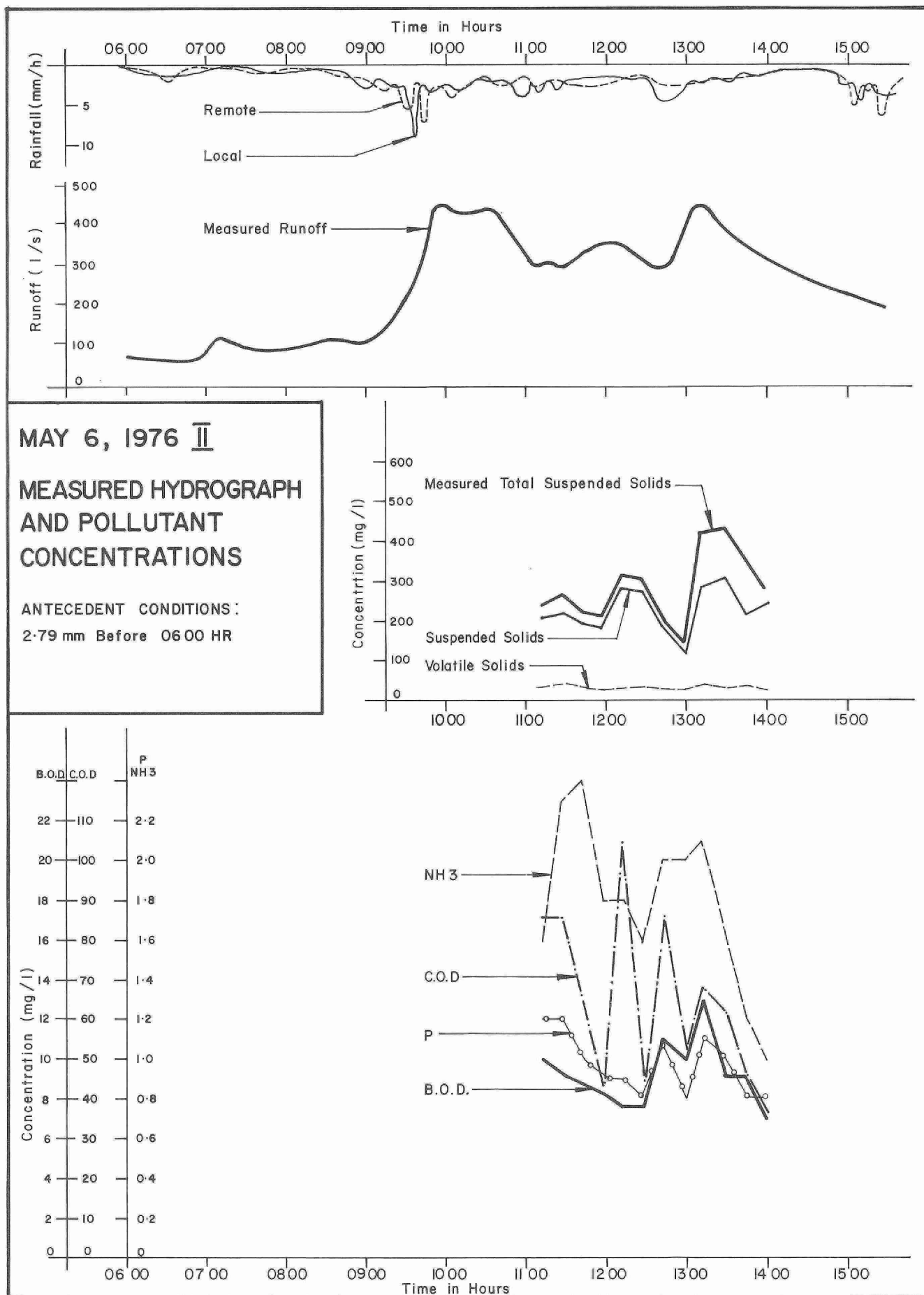


FIGURE 16. MEASURED HYDROGRAPH AND POLLUTANT CONCENTRATIONS, MAY 6, 1976 II

suspended (non-volatile) component peaked later than the volatile component, indicating that the surface washoff heavily laden with suspended sediment reached the sampler site later.

The persistence of high loads of suspended solids compared to a rapid decrease in volatile solids for longer duration events (such as May 6 I and II, and July 29 I and II, 1976, Figures 15, 16, 17 and 18) can be attributed to the influence of the construction activity. During May - August, 1976, a land area of about 5.7 ha (14 acres) at the southern end of the watershed was regraded, and this probably contributed significantly to the increases in suspended solids loads compared to volatile solids. This is illustrated by the data shown in Table 9.

It is evident that, during the construction period, the mass of suspended solids in absolute terms and in comparison to the volatile solids increased considerably for similar rainfall conditions. This aspect of the suspended solid loads, which can be considered to originate from a point source in relative terms, required special attention during the quality simulations using the SWMM program.

TABLE 9. IMPACT OF CONSTRUCTION ACTIVITY ON SUSPENDED SOLIDS LOADINGS

Date	Rainfall (mm)	Peak Flow (L/s)	Approximate load (kg)		Ratio
			Volatile Solids	Suspended Solids	<u>Suspended Solids</u> Volatile Solids
<u>Pre-construction period</u>					
October 9/75 I	1.8	70	88	29	0.33
October 9/75 II	1.3	95	85	37	0.44
November 27/75	9.4	120	114	93	0.82
December 30/75	10.2	53	26	46	1.77
April 15/76	1.0	140	273	106	0.39
April 21/76	1.3	95	112	22	0.20
<u>Construction period</u>					
May 6/76 I	2.4	110	48	60	1.25
May 6/76 II	9.0	400	21	175	8.33
May 16/76	3.3	530	321	604	1.88
July 16/76	16.3	1300	414	2655	6.41
July 20/76	3.1	180	120	80	0.67
July 29/76	6.4	340	240	2070	8.63

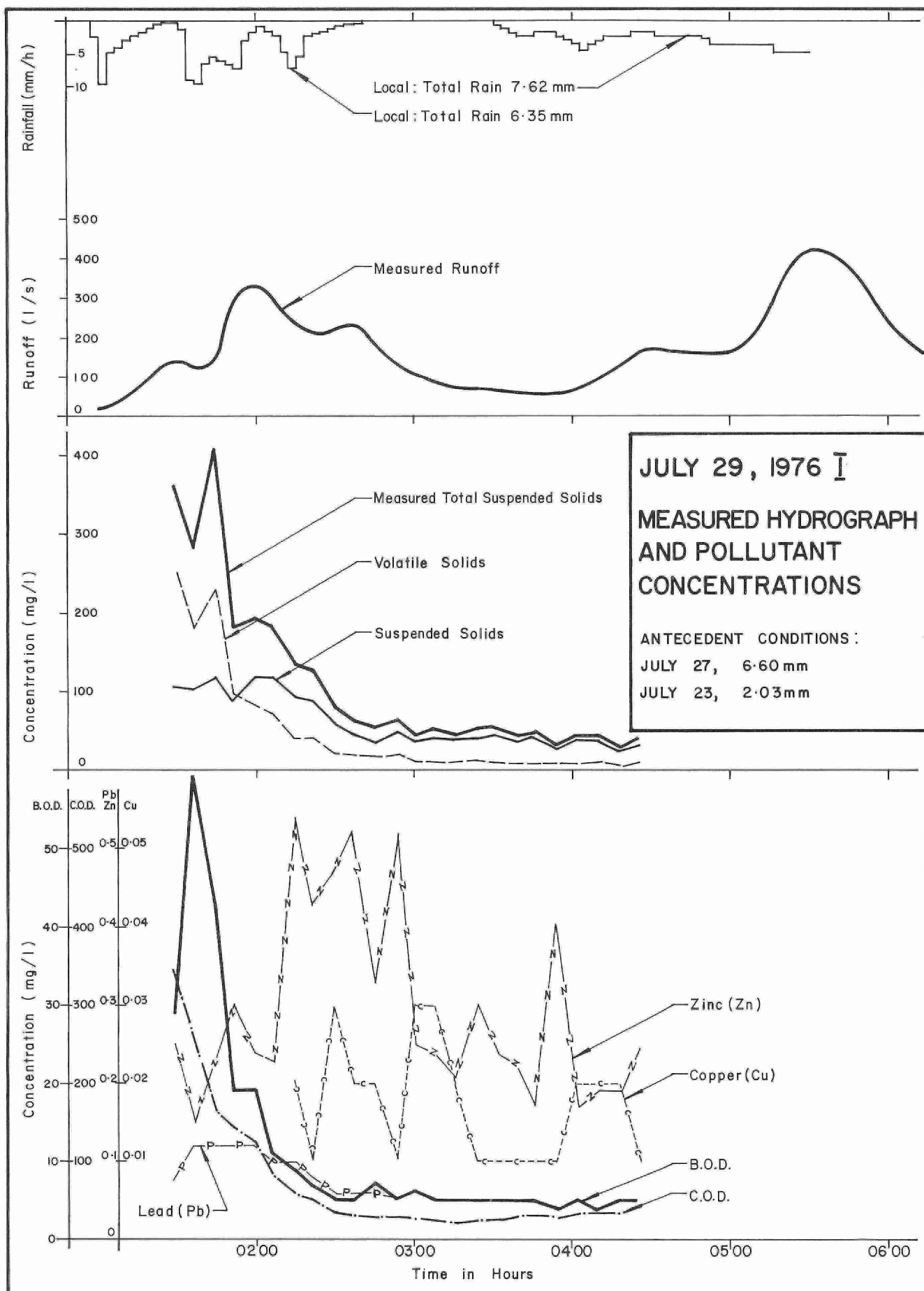


FIGURE 17. MEASURED HYDROGRAPH AND POLLUTANT CONCENTRATIONS, JULY 29, 1976 I

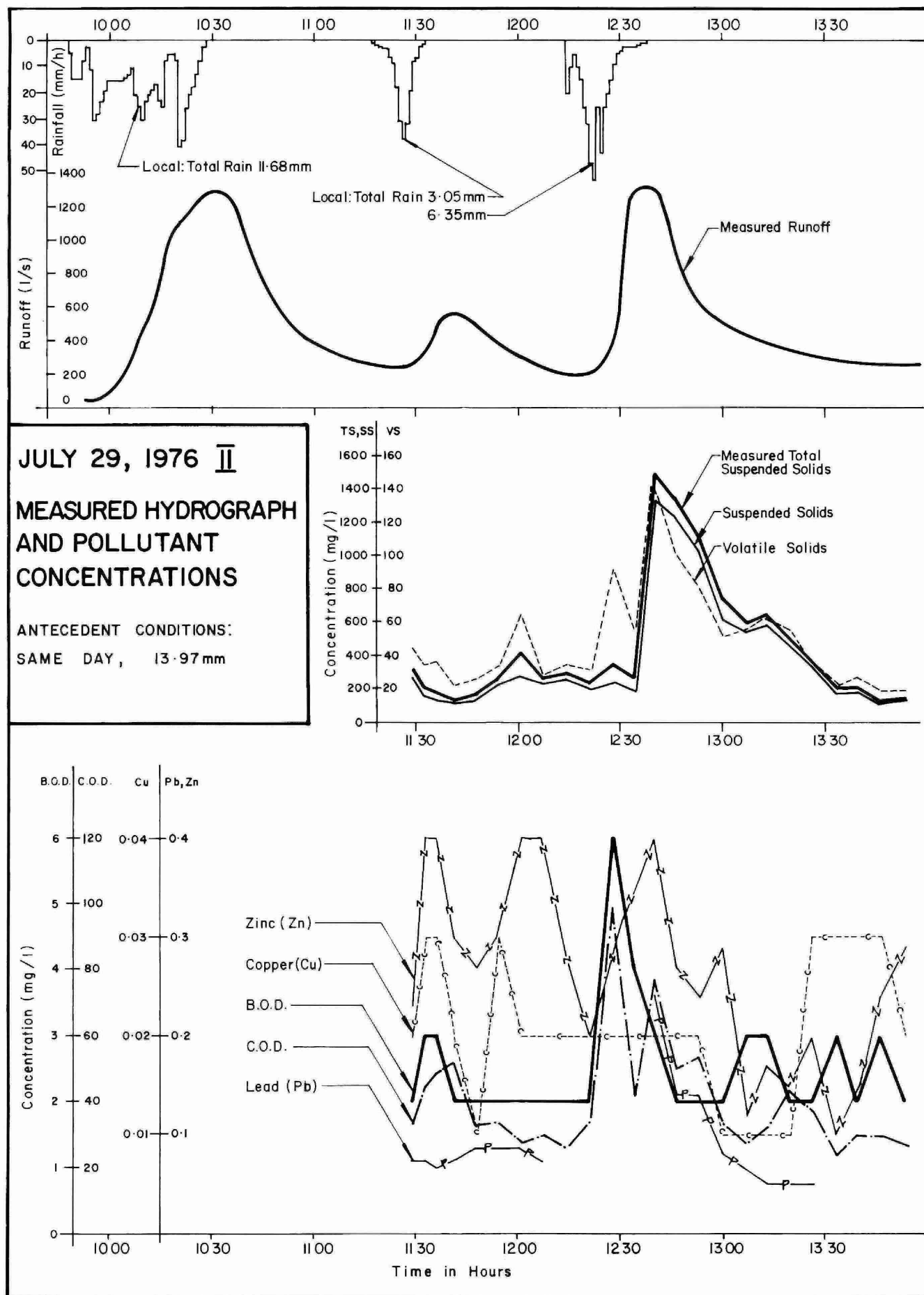


FIGURE 18. MEASURED HYDROGRAPH AND POLLUTANT CONCENTRATIONS, JULY 29, 1976 II

Certain heavy metals were tested for during the laboratory analyses to furnish some indication of the concentrations experienced during the dry and the wet weather samplings. The analysis of these constituents is not pursued further in this report. However, the results of the laboratory analyses are presented in the relevant appendices as part of the extensive data gathered during field monitoring*.

* Available as a separate volume from the Scientific Authority at the address given at the end of Section 1.

6.1 General

The SWMM program version used in this study was U.S. EPA Release II, September 1970, updated March 1976 by the University of Florida. The program and details of input data preparation were discussed in Section 4. The simulations for calibration were carried out using the RUNOFF and TRANSPORT blocks of the program; comparisons of the simulated and observed histograms are presented in this section for quantity and quality aspects of the storm runoff.

6.2 Runoff Quantity Modelling

The initial analysis of the observed results and comparative evaluation with the results of preliminary computer simulations (using the SWMM RUNOFF block) were discussed in Section 5.3. As outlined therein, this analysis provided indicators for adjusting the model parameters during the calibration process. A short discussion of these parameters and their values is presented below to stress their importance to this study.

6.2.1 Discussion of calibration parameters

The major hydrologic parameters needing adjustment were the infiltration rates and the surface detention storage. The percent imperviousness, which can be normally estimated with fair accuracy, was reviewed to ascertain the indirectly draining portion, which is normally overlooked in the initial evaluation. The overland flow width is one of the prime calibration parameters directly influencing the subcatchment response time and thereby the flow hydrograph. This parameter has most significance in coarsely discretized study areas (i.e., subcatchments of large size). The roughness factor controlling overland flow also has some effect on subcatchment hydraulic response. The base flow variations estimated for this study were based on certain assumptions; the subjective nature of the assumptions make this factor another prime calibration parameter.

There are a number of constraining conditions which influence the objectives of a study of this nature. These are instrumentation limitations in the data acquisition system, the random nature of rainfall events, and

the range of antecedent conditions, which influence the observed results but are not normally represented in the modelling process. Therefore, for a field verification study of this nature, the agreement between simulated and observed results will not be 100%. If, over a wide range of events, the model is able to generate results within 10% of observed values for important output parameters, it can be considered to be adequately verified for the given watershed.

The version of the SWMM used in this study accounts for infiltration losses by an integrated form of Horton's infiltration equation. The unsatisfied infiltration volume for each time step is taken from the rainfall volume after accounting for an initial evaporation loss of 0.01 inches/day (0.0004 inches/hour or 0.01 mm/h). Any excess precipitation has to fill the depression storage specified before runoff takes place. The infiltration potential is "recharged" during dry periods between two rains up to its maximum value. Both the value for initial evaporation and the regeneration rate are fixed in this model version, whereas later releases allow adjustment of these parameters to account for local and seasonal variations. This approach is based on the assumption that, for single event runoff simulations using the SWMM, the potential base flow increases are normally minimal. However, if accurate infiltration data is available for the watershed, the program has an "infiltration module" to model these extraneous inflows.

In this study, as explained earlier, it was found that especially for long duration events with large rainfall volumes, there is a very significant increase in base flow which is more evident with the progress of the storm. Since a direct approach to estimating these extraneous flows was not available, it was thought that the simulation results would increase runoff for large storms by reducing the infiltration potential and the consequent percolation losses. This approach might lead to over-estimated runoff for low volume storms; however, since the SWMM is oriented towards simulating higher volume rains, which are more critical for a given drainage system, this approach was considered valid for this study. Furthermore, the detention storage parameter can be adjusted to simulate minor storms. The results of a brief literature survey on

values assigned for infiltration rates and depression storage during previous studies by different authors are included as background information.

The SWMM default values which were used in the initial simulation were: minimum infiltration rate of 13.2 mm/h (0.52 inches/hr); maximum infiltration rate of 76.2 mm/h (3.0 inches/hr); and decay rate (the coefficient of "exponential time parameter") of 0.00115 sec^{-1} . It is noted that Pecher, from field measurements of urban runoff in a study area in Germany, suggested values of 3.6-7.2 mm/h (0.14-0.28 inches/hr) for minimum infiltration, about eight times this value for maximum rate, and a decay rate of 0.00108 sec^{-1} [7,8,9]. These values are reasonably close to SWMM default values at the higher range and about half for the lower rates.

Depression storage is defined as the volume of water expressed as depth on the entire surface of the area which is required to fill natural depressions, large or small, to their overflow levels. This parameter is important for calibration of the RUNOFF block, in particular for minor rainfall-runoff events, since runoff from impervious areas commences only after filling the depression storage and from pervious areas subsequent to satisfying both depression storage and infiltration losses. The SWMM uses a default value of 0.062 inches (1.57 mm) depth and 25% zero detention on the impervious area in calculating depression volume for impervious areas.

For an urban residential area in Germany, Pecher [9] derived depression storage values of 0.6 to 0.8 mm (0.023 to 0.03 inches) from data collected over three years.

Waller et al [10] determined the depression storage depth to be 0.94 mm (0.037 inches) on a predominantly residential watershed of 167 acres (68 ha). This value was based on the results of a regression analysis of about 15 storm events recorded from May to August in 1970. The work was related to SWMM studies and used an overall impervious value of 34 percent and the default value of 25 percent for the impervious area with zero detention.

6.2.2 Results of calibration

A number of test runs for some rain events covering a wide range of rainfall volumes were carried out for parameter calibration. Details of parameter adjustments made and the rainfall events used are tabulated in Table 10. As explained in the previous paragraphs, the program default values were modified during some of the simulations. Thus, apart from reducing infiltration rates, the subcatchment widths and zero detention areas, the initial impervious area was reduced by 6% to allow for indirectly drained impervious areas identified during field re-evaluation. The depression storage value was increased slightly to 1.97 mm (0.078 inches) to achieve lower runoff volumes for low-level storms as observed.

These results are plotted on Figure 19 to demonstrate the effects of the calibration process on the simulated "volumetric runoff quotient" (see section 5.3) as compared to the measured values derived by subtracting base flows from observed hydrographs. The graphical plot shows that, for higher rainfall, the calibrated values given by curve C agree more closely with curve A, representing the measured values, than with curve B, representing the initial uncalibrated results. This improvement in simulation is illustrated well in Figures 20, 21, 22 and 23 for the events of April 24-25, 1976, which was a long duration low-intensity storm, and October 6-7, 1976, with three separate rainfalls of high intensities. For the long duration storms, the simulated values increased after calibration, and for the short duration higher-intensity rains, the values decreased. Thus, for both types of rainfall events, the calibrated results were closer to the measured values, with peak flow deviations of 3% to 20% and runoff volume deviations of 2% to 14%.

As shown in Table 10, a few events were modelled using both the RUNOFF and TRANSPORT blocks; the outputs indicated that there was no consistent deviation in the response of the watershed in comparison to the earlier results using the RUNOFF block only. Only minor variations occurred in the peak flows and hydrograph shapes, as described below for three different storms.

The combined event of October 6-7, 1976, was simulated with the same parameters as above using both RUNOFF and TRANSPORT. While the first

TABLE 10. CALIBRATED SIMULATION RESULTS

		Infiltration Rate (in/hr)	Impervious Factor	Zero Detention (%)	Flow- Width Factor	Rainfall Volume (m ³)	Infiltration Volume (m ³)	Surface Storage Volume (m ³)	Runoff Volume		Runoff Quotient		Peak Flow	
									Measured (m ³)	Simulated (m ³)	Measured	Simulated	Measured (L/s)	Simulated (L/s)
March 25/76	Initial run	3.00/0.52		25		5705	3646	306	1510	1782	.265	.312	260	325
	Modified rain	3.00/0.52		25			3645	306		1777		.311		315
April 24-25/76	Initial run			25		47343	18512	278	23505	18512	.497	.391	900	750
	RUNOFF block	1.20/0.10		25			24712	278		22486		.475		925
	RUNOFF block	1.20/0.10	0.94	40			25574	209		21694		.458		900
September 17-18/76	Initial run	3.00/0.52				25730	16207	299	8280	9392	.318	.365	600	725
	RUNOFF block	1.20/0.10	0.94	40	0.50		16810	283		8851		.344		670
	TRANSPORT block	1.20/0.10	0.94	25	0.75		16782	281		8836		.343		690
October 6-7/76	Total event (3 rains)													
	Initial run	3.00/0.52		25		8670	5524	315	2440	2883	.281	.333		
	Modified rain	1.20/0.10	0.94	40			5732	232		2787		.321		
	RUNOFF block	1.20/0.10	0.94	40	0.50		5732	235		2828		.326		
	TRANSPORT block	1.20/0.10	0.94	25	0.75					2780		.320		
October 6-7/76 I	Initial run	3.00/0.52		25		1970			365	420	.185	.213	170	220
	RUNOFF block	1.20/0.10	0.94	40						413		.209		245
	RUNOFF block	1.20/0.10	0.94	40	0.50					446		.226		205
	TRANSPORT block	1.20/0.10	0.94	25	0.75					198		.100		120
October 6-7/76 II	Initial run	3.00/0.52		25		3115			905	1150	.290	.369	565	735
	RUNOFF block	1.20/0.10	0.94	40						1014		.326		680
	RUNOFF block	1.20/0.10	0.94	40	0.50					1092		.350		615
	TRANSPORT block	1.20/0.10	0.94	25	0.75					1239		.342		665
October 6-7/76 III	Initial run	3.00/0.52		25		3580			1170	1315	.327	.367	540	670
	RUNOFF block	1.20/0.10	0.94	40						1188		.332		625
	RUNOFF block	1.20/0.10	0.94	40	0.50					1239		.346		600
	TRANSPORT block	1.20/0.10	0.94	25	0.75					1262		.352		660

All peak flows include base flow (DWF, sewer infiltration).

All volumes are net values, excluding any base flow.

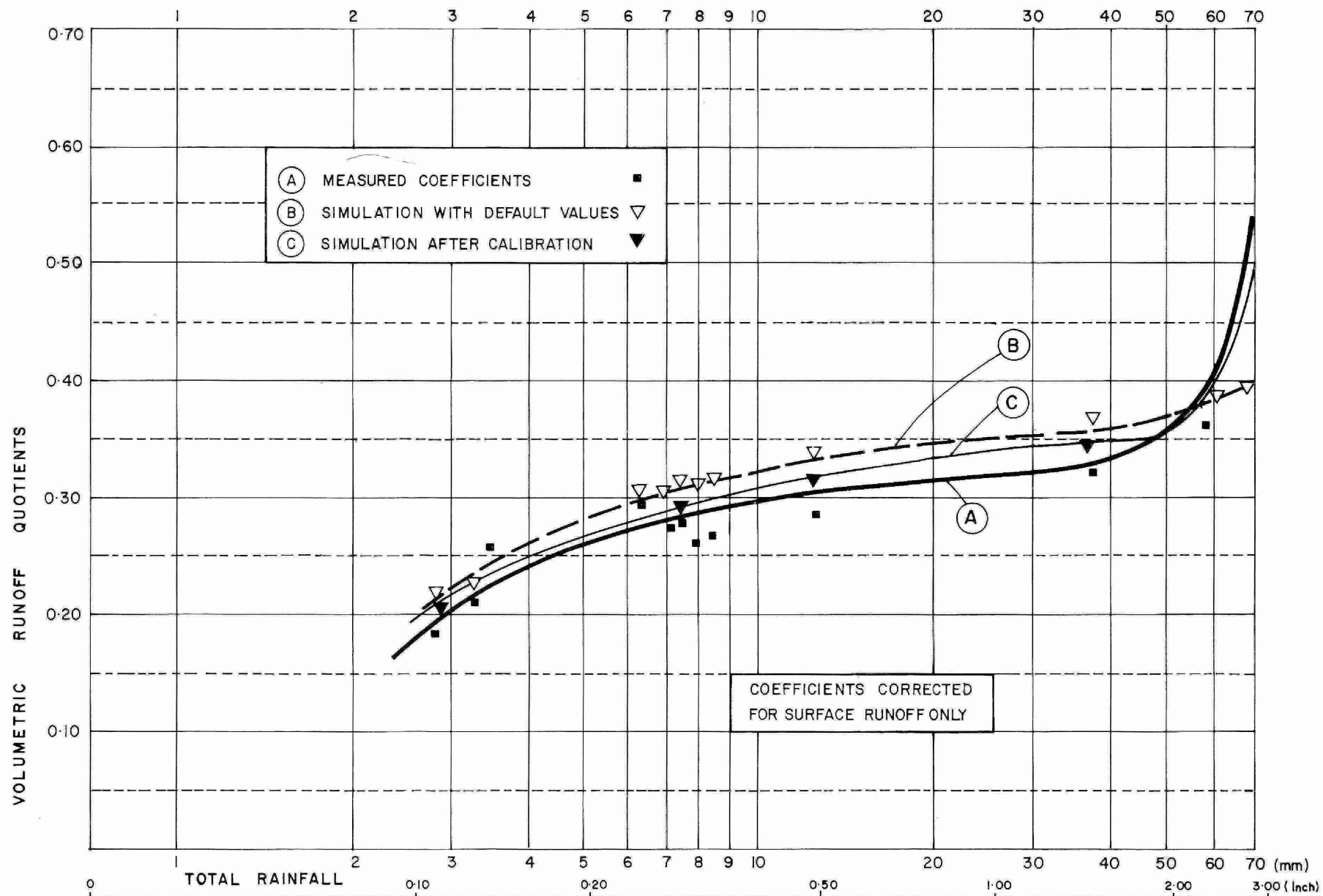


FIGURE 19. COMPARISON OF OBSERVED AND SIMULATED VOLUMETRIC RUNOFF QUOTIENTS

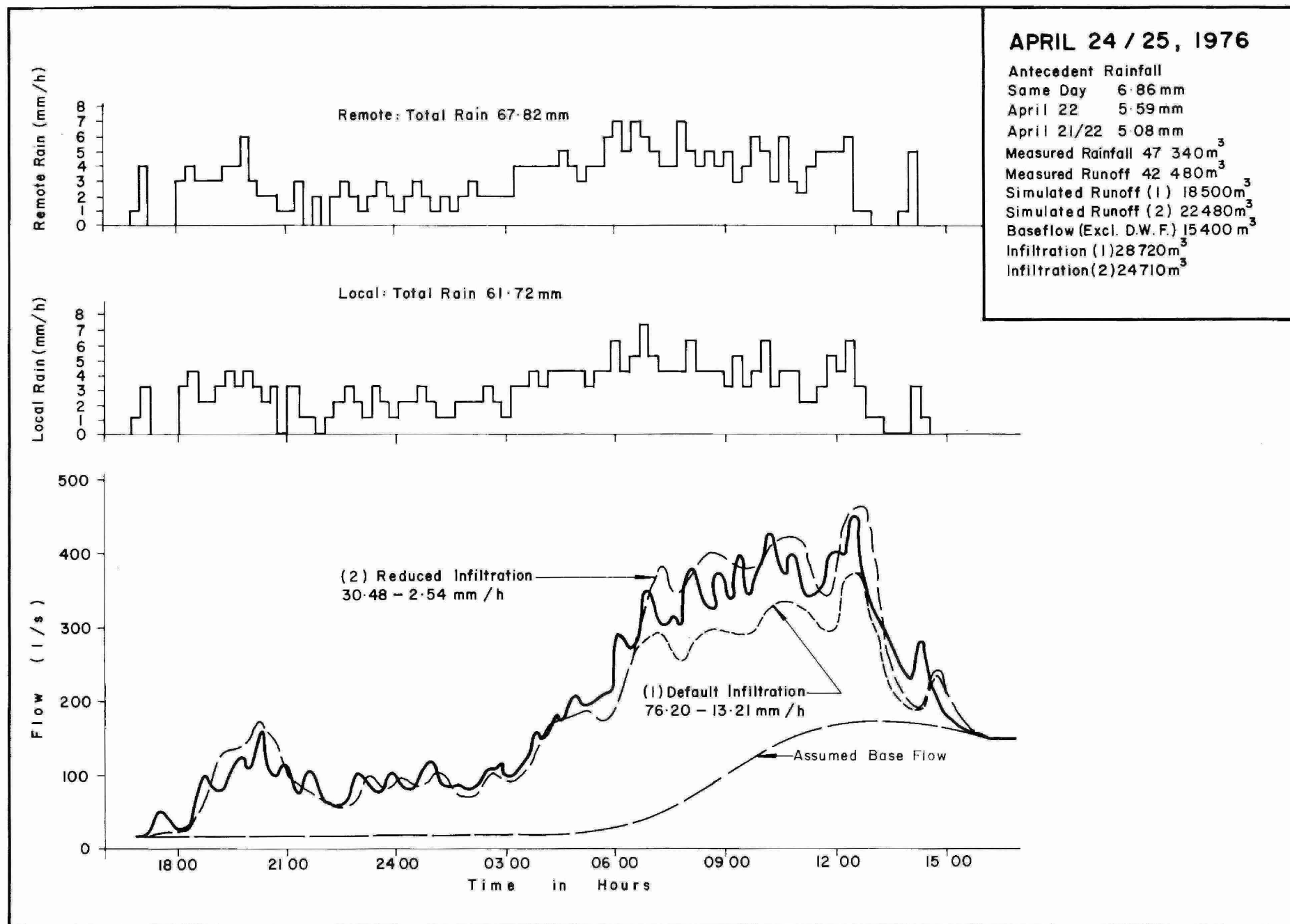


FIGURE 20. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, APRIL 24-25, 1976

OCTOBER 6/7 1976 I

Antecedent Rainfall

Sept. 25 11.68 mm

Sept. 23 3.30 mm

Measured Rainfall 1970 ³m

Measured Runoff 330 ³m

Simulated Runoff 420 ³m

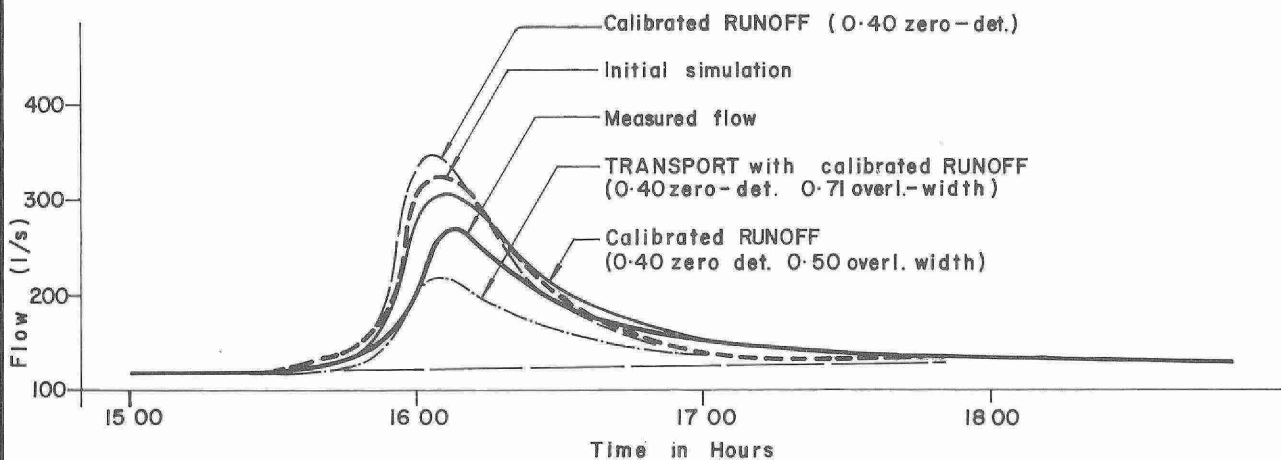
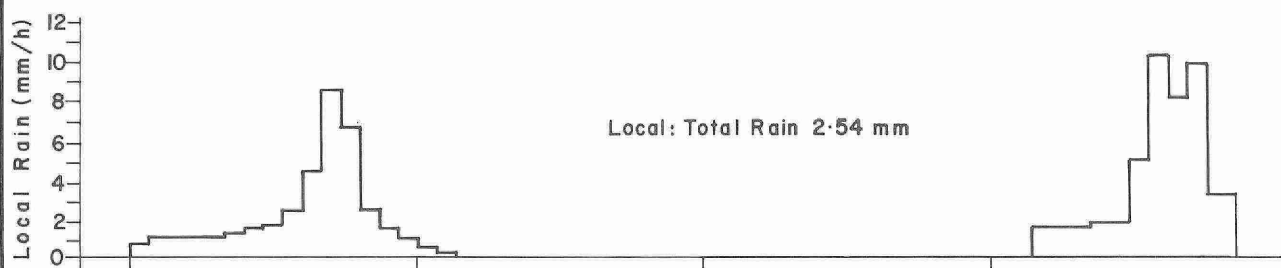
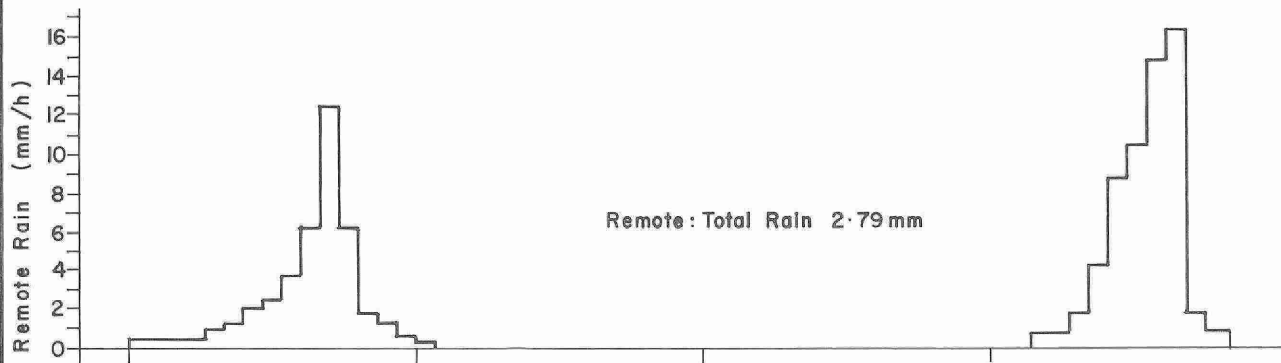


FIGURE 21. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, OCTOBER 6-7, 1976 I

OCTOBER 6/7 1976 II

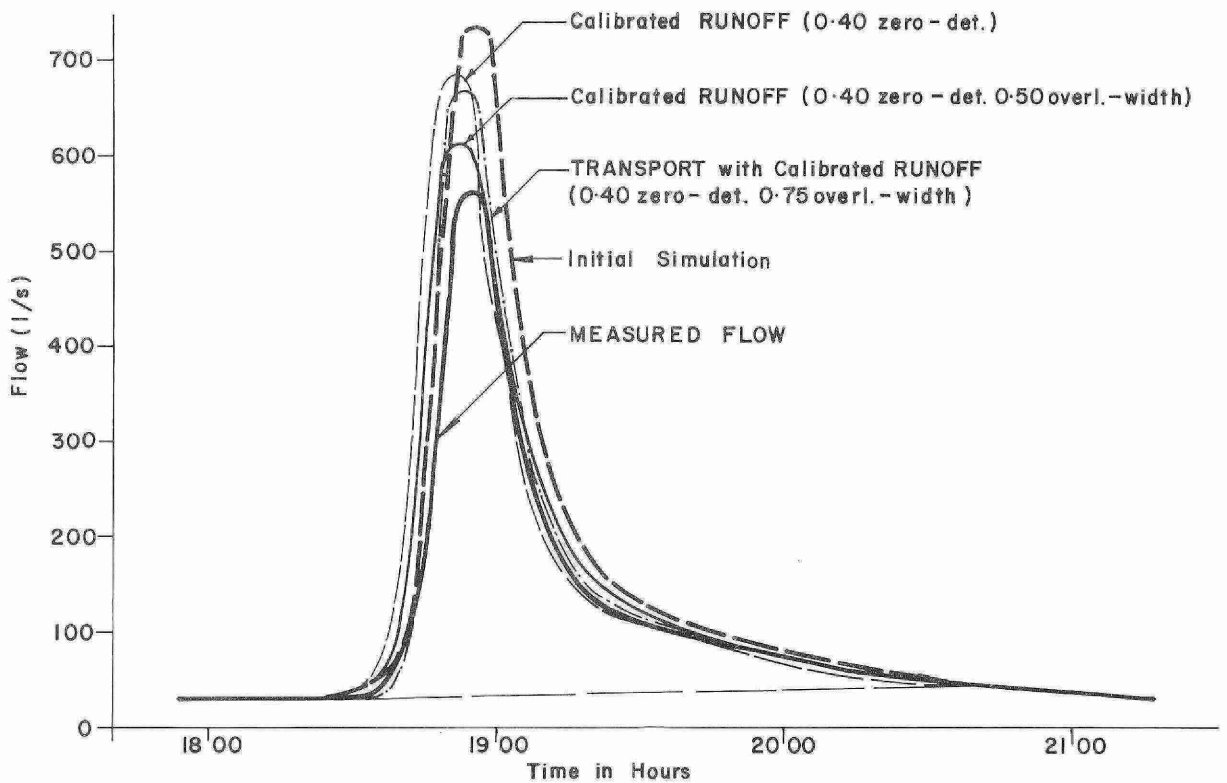
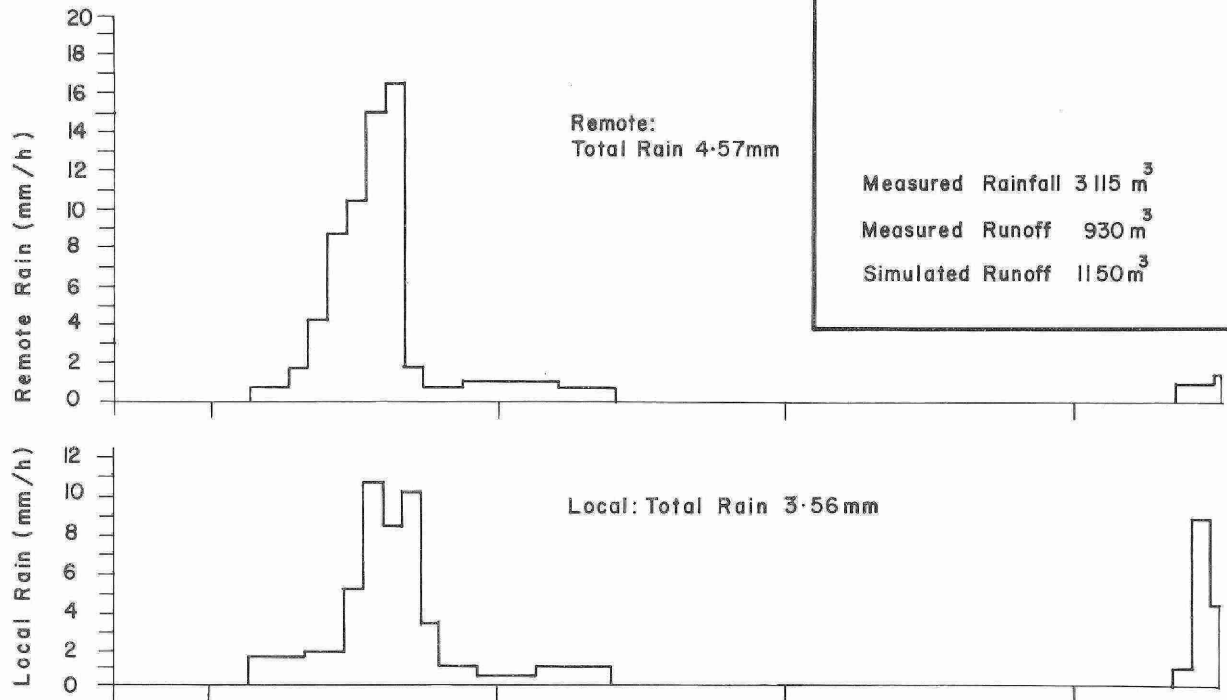


FIGURE 22. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, OCTOBER 6-7, 1976 II

OCTOBER 6/7, 1976 III

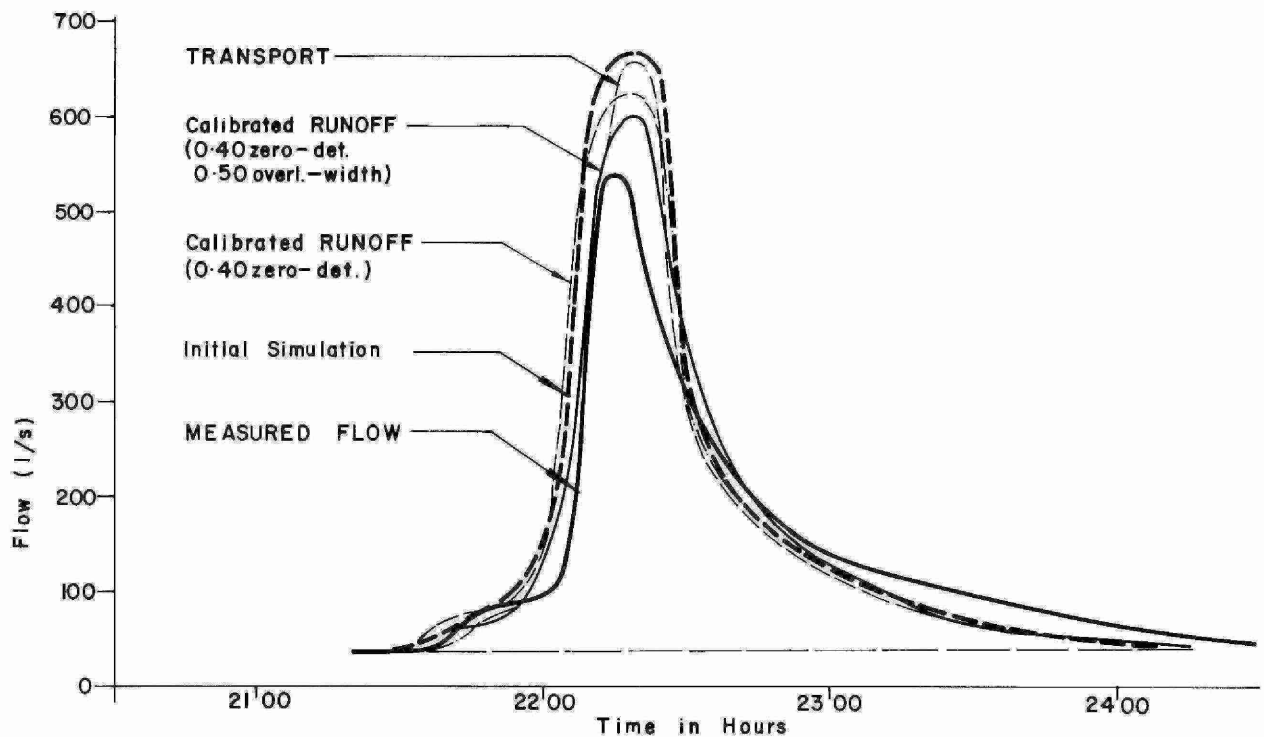
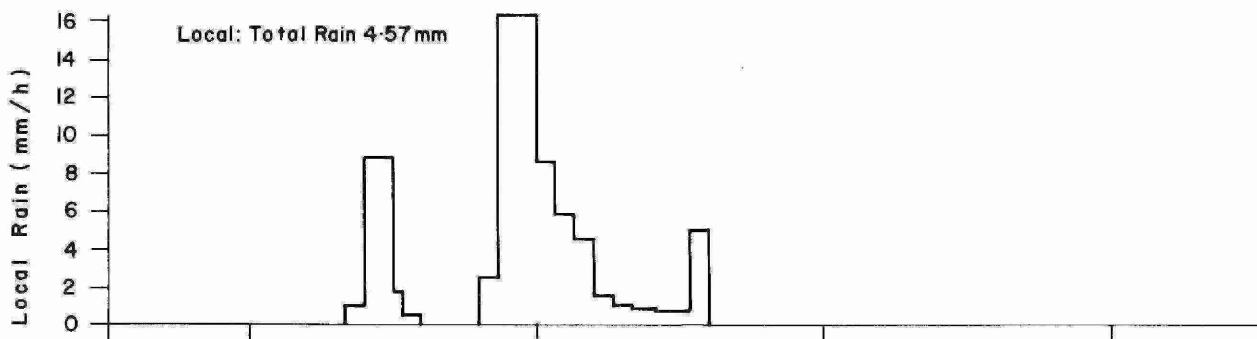
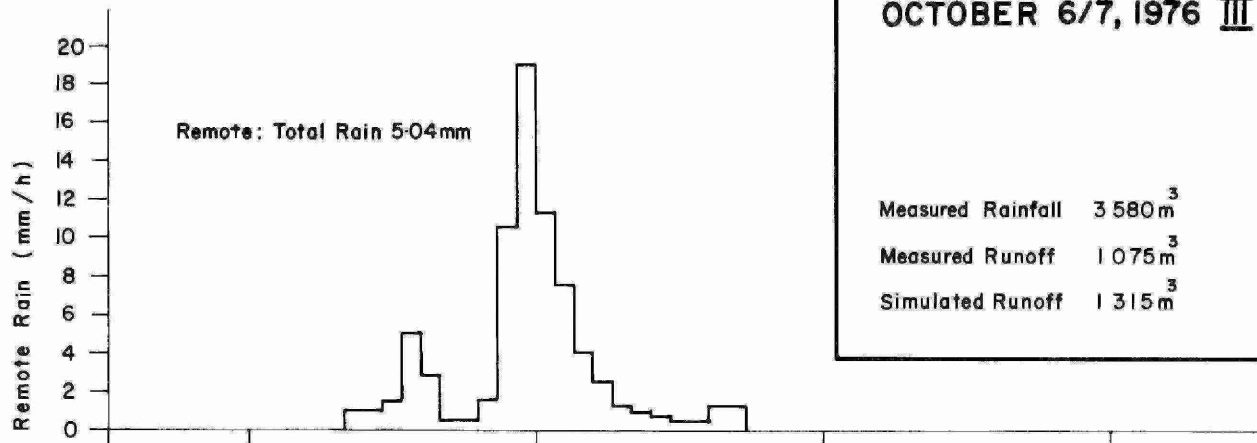


FIGURE 23. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, OCTOBER 6-7, 1976 III

and second storm hydrographs were accelerated in comparison to the initial RUNOFF simulation, the third storm showed the rising limb of the hydrograph delayed by three to four minutes. Simulation using the RUNOFF block only with further reduced overland flow width (factor 0.5) produced less attenuation, excluding this as a possible cause. Both alternatives are shown in Figures 21, 22 and 23.

The prolonged event of September 17-18, 1976, was modelled with the TRANSPORT block using modified parameters in the RUNOFF block (infiltration 0.10 to 1.20 inches/hour, imperviousness reduced by 6 percent and a factor of 0.75 applied to the initial overland flow width). Here, the hydrograph was delayed compared to the initial run, and had lower peaks. A RUNOFF simulation with the same parameters but with a reduction factor of 0.50 for the overland flow width produced even more attenuation, which indicated that the major difference resulted from the runoff block input parameters. These results are shown in Figure 24.

Also modelled using the TRANSPORT block were the two events of May 16, 1976, using the uncalibrated RUNOFF input data. Both hydrographs responded slightly faster. The morning storm matched almost perfectly with the measured runoff. The afternoon storm hydrograph appeared to be shifted to five minutes ahead in time with slightly higher peak flow. Two secondary rain events were about 10 minutes too early and yielded larger outflows compared to the measured runoff. Figure 25 illustrates the results of event II.

These results indicated that the sensitivity of the SWMM simulation output value was closely related to values assigned for RUNOFF block input parameters. Therefore, during calibration of the model, preferably, the RUNOFF block parameters should be the variables so that an improved representation of the process of runoff generation is achieved by the model.

Following the data collection period in 1977, an additional 15 rainfall-runoff events were selected and simulated using the RUNOFF block only. For these simulations, the input data was modified to include only that part of the watershed and the system remaining after the disconnection of the separate sewers on Carson Drive. The resulting area comprised 54.72 ha (135.22 ac) with an average imperviousness of 41.8 percent.

SEPT. 17 / 18, 1976

Antecedent Rainfall

Sept. 11 3.81 mm

Sept. 10 3.30 mm

Measured Rainfall 26 000 m³

Measured Runoff 8 280 m³

Simulated Runoff 9 392 m³

Assumed Base Flow 4 590 m³

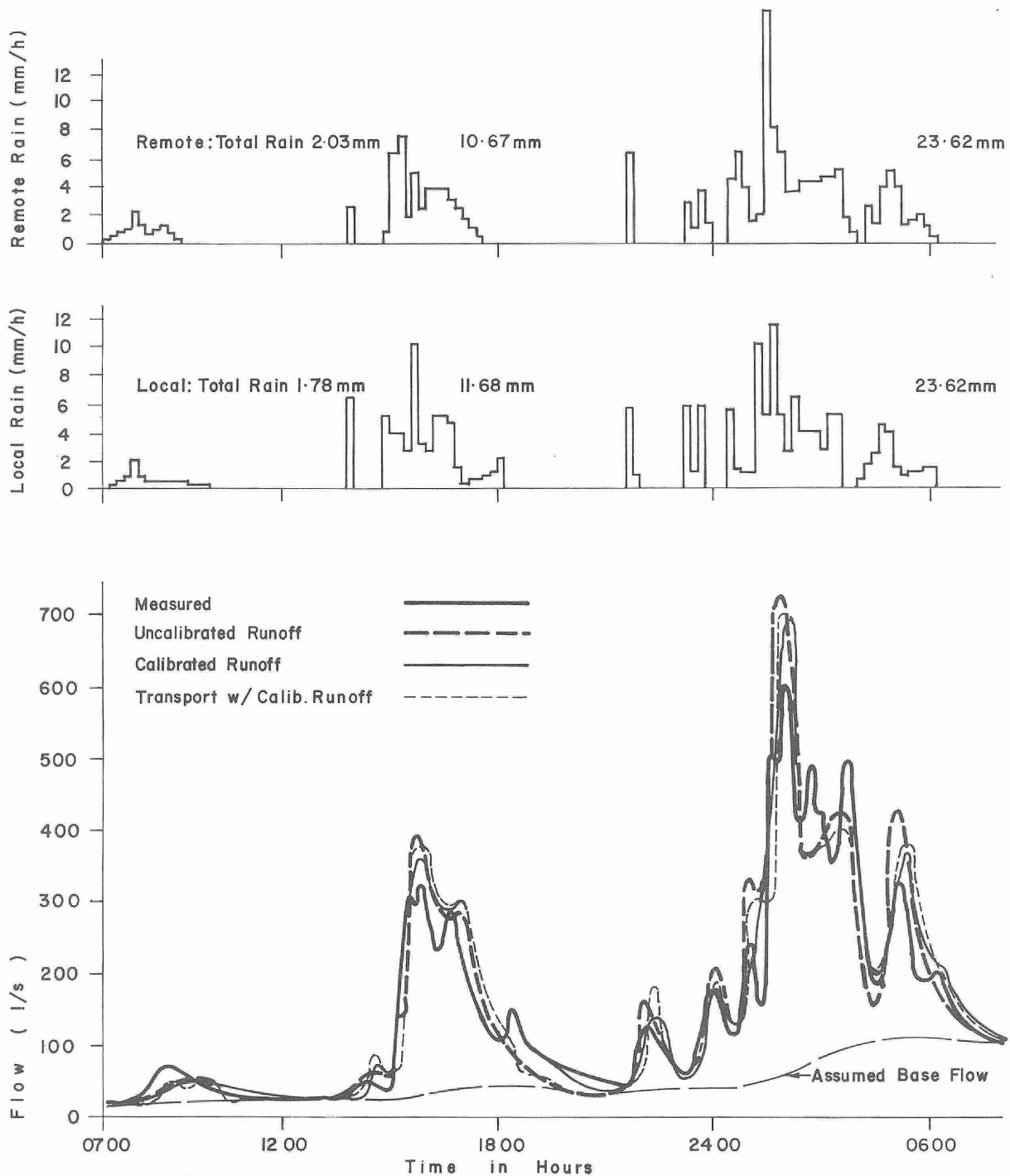


FIGURE 24. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, SEPTEMBER 17-18, 1976

MAY 16, 1976 II

Antecedent Rainfall

Same Day 10.92 mm

May 11 7.37 mm

May 6 / 7 56.39 mm

Measured Rainfall 4 895 m³

Measured Runoff 1 340 m³

Simulated Runoff 1 495 m³

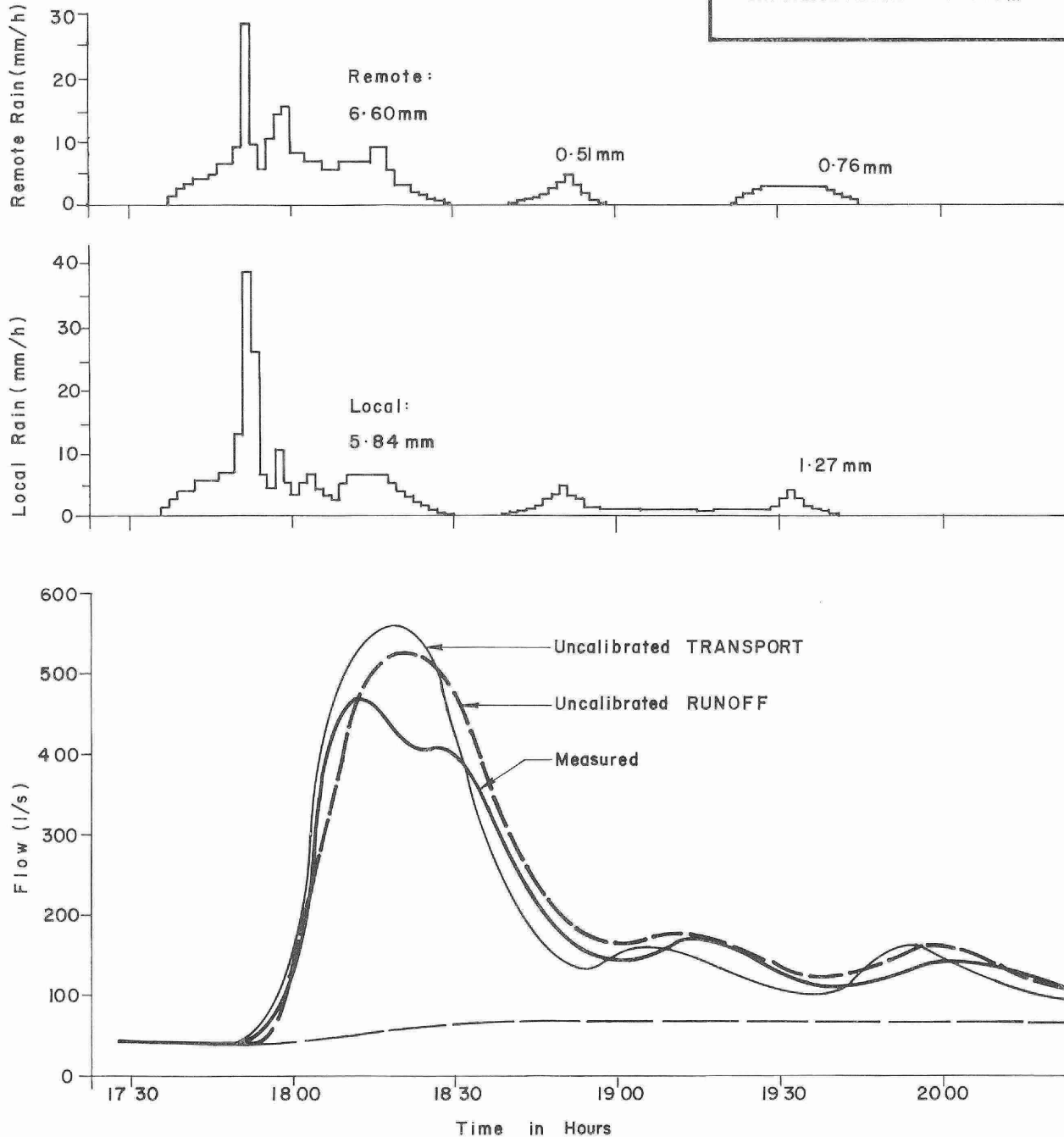


FIGURE 25. COMPARISON OF OBSERVED AND SIMULATED HYDROGRAPHS, MAY 16, 1976 II

Hyetograph data for the 15 rainfall events were obtained from both rainfall recorders. The hyetographs demonstrated the substantial differences in the rainfall patterns for the more violent storms. The results of the simulations differed from observed values to various extents; in general, the disagreements increased for low volume storm events. Attempts to remodel certain events with better discretization failed to improve the level of matching with the measured hydrographs.

6.2.3 Verification of calibrated model

The selected rainfall-runoff events were simulated using the calibrated values from 1976 data analysis for the input parameters in place of the default values, except for depression storage which had been reduced to the default value of 1.57 mm (0.062 inches). These results and the observed values are plotted on Figure 26, which shows that the simulated values produced an upper limit envelope curve which tends to agree with observed values for thunderstorm events. Therefore, there was an indication that earlier calibration efforts helped to produce a calibrated model that was weighted towards predicting runoff from intense storms. The fairly wide scatter of the observed results seen in Figure 26 appears to indicate variations in aerial distribution of rainfall from the values at the two gauges. In addition, all these events had rainfall volumes less than 10 mm, which is a constraint, since calibration was oriented towards better simulation of higher volume rainfalls.

6.2.4 Quantity simulation conclusions

In summary, these detailed analyses, from initial simulations to calibration and the final results using 1977 data, demonstrated that the SWMM could produce reasonably accurate hydrographs during initial rainfall-runoff simulations provided the rainfall data and the physical system modelling data were prepared using reliable plans supported by field confirmations. This level of prediction was further improved by a process of proper calibration. Furthermore, the methodology of calibration and verification (which is complex due to the large number of parameters involved) can itself be improved and better defined for future use as a direct result of the difficulties encountered in this exercise. In this context, a number of recent results presented at SWMM user conferences and other literature have become available for better guidance of future efforts in this difficult exercise.

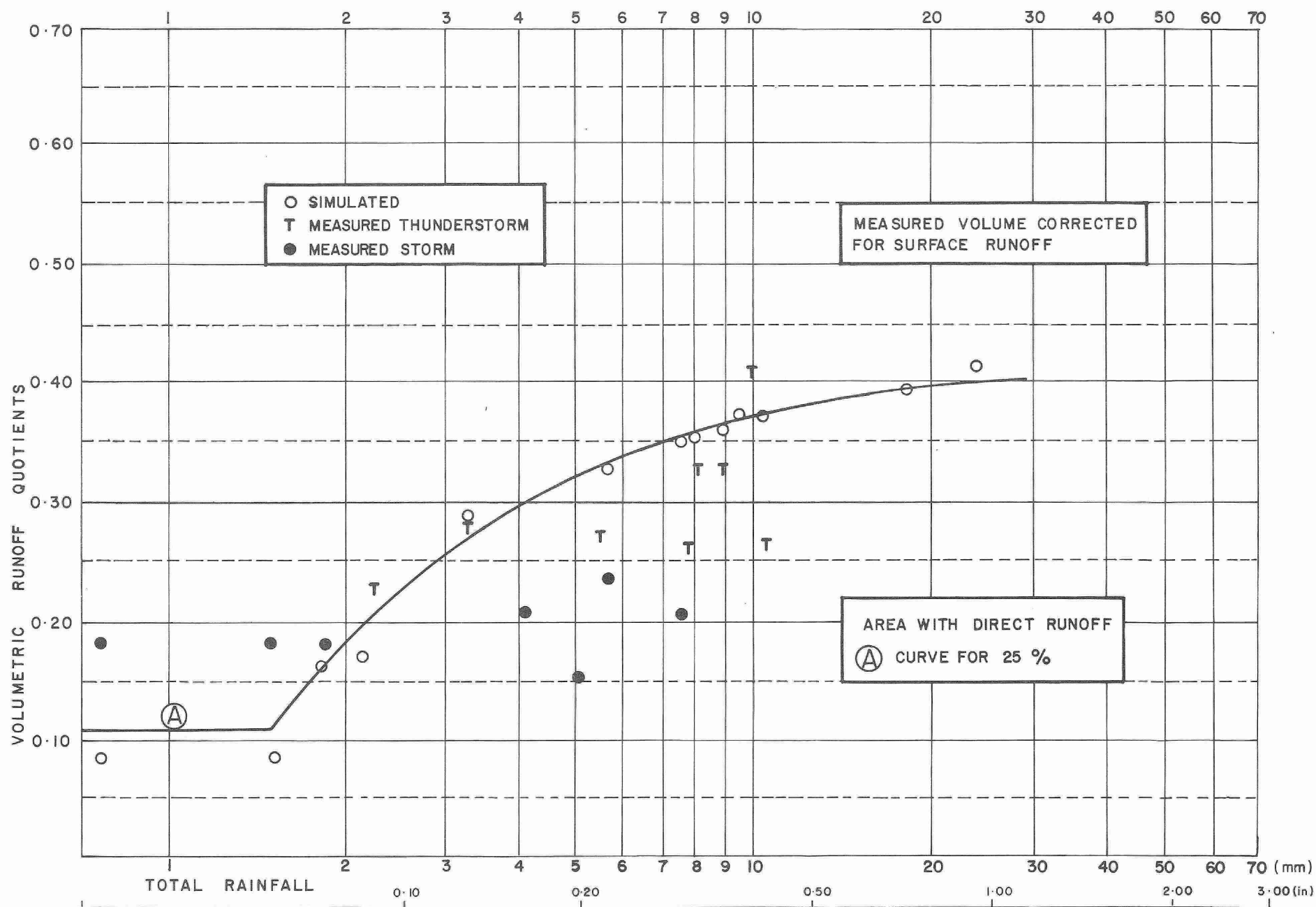


FIGURE 26. COMPARISON OF OBSERVED AND SIMULATED VOLUMETRIC RUNOFF QUOTIENTS

6.3 Runoff Quality Modelling

6.3.1 General

The purpose of quality simulations was to obtain single-event based pollutographs similar to those observed. The methodology of calibration adopted was basically the same as that for hydrograph simulations described earlier. The calibrated RUNOFF and TRANSPORT block data were used for generation of the runoff. The default values described in Section 4, and given in Tables 1 and 2, were initially adopted for the generation of pollutant loadings from surface washoffs, resuspension of sewer-deposits and the catch basin loads. The dry weather flow data were based on the observed values.

6.3.2 Quality simulation with RUNOFF and TRANSPORT blocks

Initial quality simulations were carried out for two events: May 16 (I) and July 20-21, 1976, using the RUNOFF and TRANSPORT blocks. The maximum antecedent dry days of 5 and 20, respectively, were used for these events on the basis of the observed rainfall given in Table 11 and the SWMM data requirement of antecedent time in days for which cumulative rainfall is 25.4 mm (1.0"). The results are given in detail in Appendix H* and the relevant graphical plots are in Figures 27 and 28. The parameters SS and BOD were selected as basic indicators of pollutorial impact on sewer flows from surface washoff during runoff-generating rainfall events. The comparison of concentrations was adopted because the observed and simulated hydrographs used in computing mass loading rates are given in these figures. The results show that the simulated pollutographs for both constituents were considerably lower in value and occurred significantly earlier than the observed values. The simulated SS concentration was 110 mg/L compared to an observed value of 2000 mg/L for the May 16 event and it occurred about 40 minutes before the flow hydrograph responded to the impact of the storm. This marked difference in timing of first flush effect for suspended solids was common to both simulations.

In an effort to improve the simulations, the May 16 event was remodelled with increased dry weather periods of 20 days in the RUNOFF and

* Available from the Scientific Authority at the address given at the end of Section 1.

TABLE 11. ANTECEDENT RAINFALL CONDITIONS FOR QUALITY SIMULATIONS

Rainfall Event	Antecedent Rain Event	Antecedent Dry Days	Rainfall in Inches			
			Remote Gauge		Local Gauge	
			For Event	Cumulative	For Event	Cumulative
May 16/76		0	0.12	-	0.14	-
	May 11 p.m.	5	0.10	0.10	0.10	0.10
	May 11 p.m.	5	0.29	0.39	0.29	0.39
	May 6-7	9½	2.12	2.51	>2.0	>2.29
	May 6 a.m.	10	0.10	2.61	0.09	>2.38
	May 2-3	13½	0.26	2.87	0.27	>2.65
	April 24-25	21½	2.73	5.60	2.5	>5.15
July 20-21, 1976		0	0.11	-	0.13	-
	July 16	4	0.76	0.76	>0.70	>0.70
	July 14-15	6	0.03	0.79	0.03	>0.73
	July 10	10	0.19	0.98	0.20	>0.93
	July 3	17	0.03	1.01	0.03	>0.96
	July 2	18	0.07	1.08	0.06	>1.02
	July 1	19	0.38	1.46	0.34	>1.36
	June 30	20	0.39	1.85	0.37	>1.73
Sept. 17-18 1976		0	0.42	-	0.42	-
	Sept. 17 a.m.	0	0.03	0.03	0.06	0.06
	Sept. 11	6	*	-	0.15	0.21
	Sept. 10	7	*	-	0.13	0.34
	Aug. 28	28	*	-	0.07	0.41
	Aug. 14-15	33	*	-	0.54	0.95
	Aug. 13	34	*	-	0.06	1.01
	Aug. 12	35	*	-	0.14	1.15
	Aug. 8-9	39	*	-	0.28	1.43
	Aug. 7-8	40	*	-	0.13	1.56
	Aug. 7	41	*	-	0.21	1.77

* Rain gauge out of order.

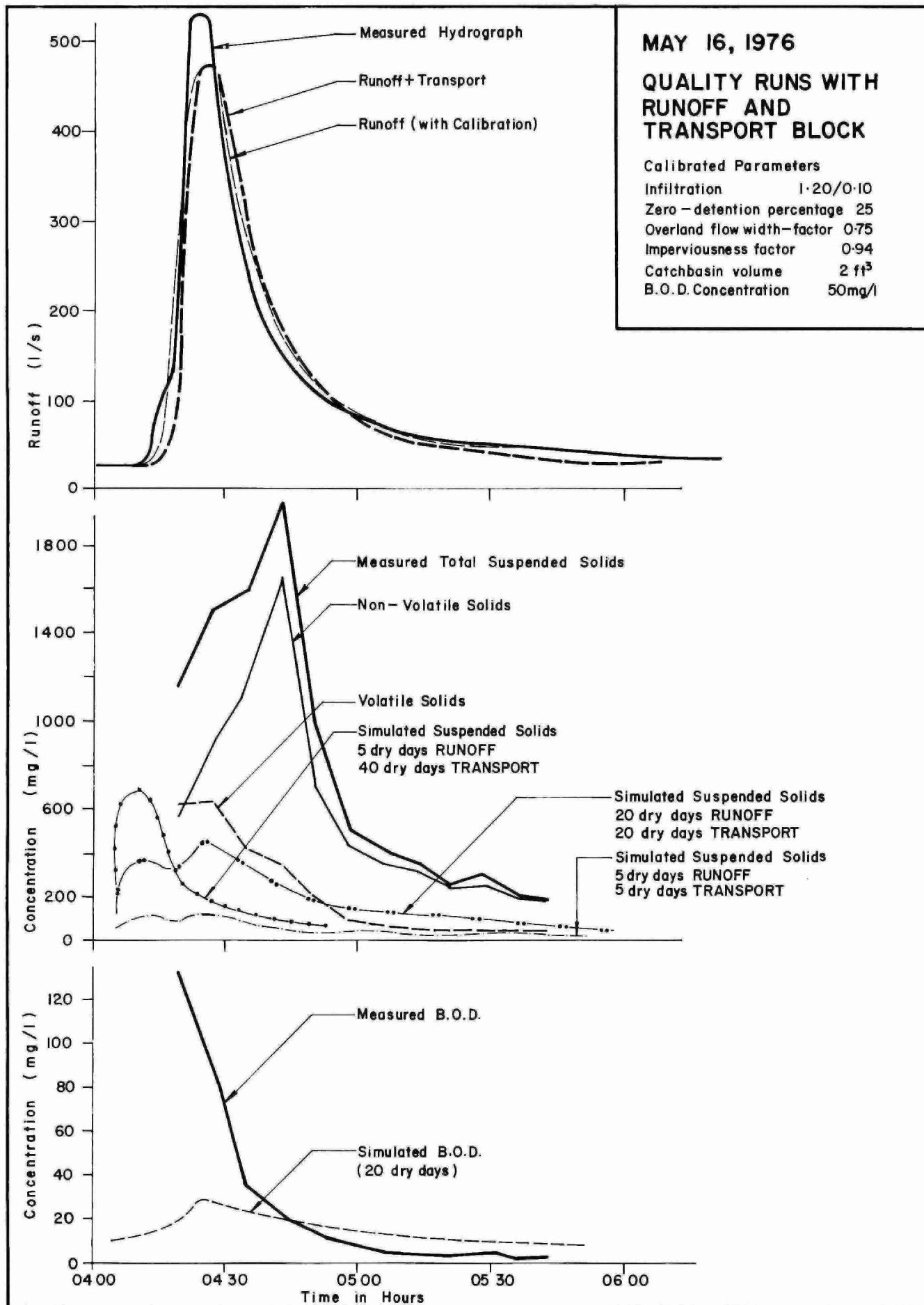


FIGURE 27. QUALITY RUNS WITH RUNOFF AND TRANSPORT BLOCKS MAY 16, 1976

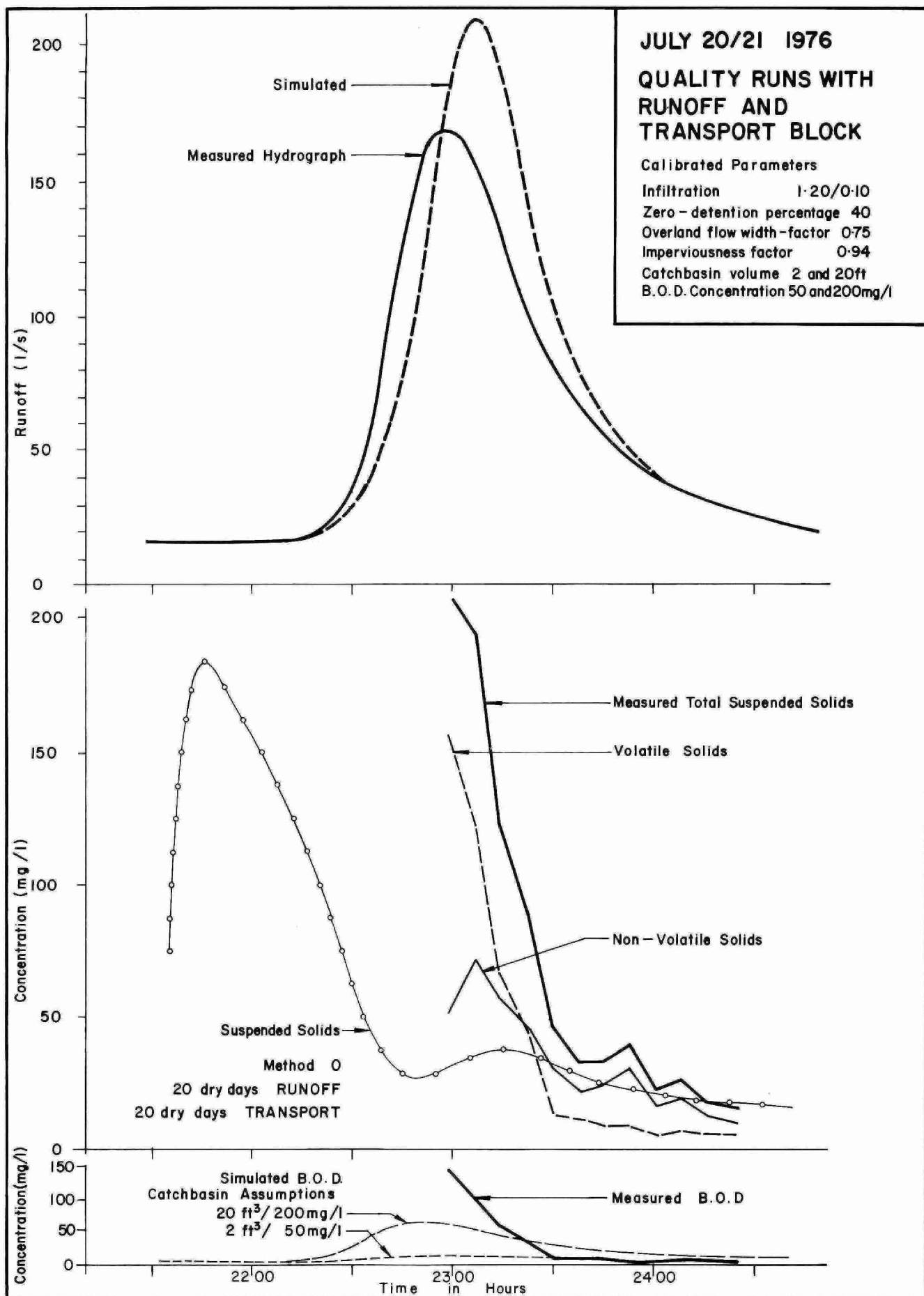


FIGURE 28. QUALITY RUNS WITH RUNOFF AND TRANSPORT BLOCKS JULY 20-21 1976

TRANSPORT blocks for one 'run', and 5 days in RUNOFF block and 40 days in TRANSPORT block for another 'run'. These results are also given in Figure 27 for SS loadings; although the maximum concentration increased to 675 mg/L, still only about 34% of observed value, the timing did not improve. Only the maximum simulated BOD result of 30 mg/L concentration for the extreme assumption of 20 days is plotted on Figure 27. This is only about 20% of the observed value of 140 mg/L.

The July 20-21, 1976, event was re-run with increased values for catch basin volumes and BOD concentrations. The results are tabulated below for BOD only since these changes did not affect the SS loadings in this program version.

Catch Basin Volume (ft ³)	Catch Basin BOD Concentration (mg/L)	Total BOD (RUNOFF block) (lbs)	Peak Concentration (TRANSPORT block) (mg/L)
2	50	17.15	14.1
20	200	61.3	64.7

The BOD concentrations increased about $4\frac{1}{2}$ times using a ten-fold increase in catch basin volume and a four-fold increase in initial catch basin BOD concentration. Even so, the results are lower than the observed values shown in Figure 28.

These initial simulation and calibration results using the SWMM RUNOFF and TRANSPORT blocks indicated the following:

- a) Even using simulated values as high as four times the actual dry weather days, the model predicted concentrations for BOD and SS notably lower than the observed values.
- b) The timing of peak suspended solids concentration occurred much earlier than the observed and simulated hydrographs and the observed pollutograph, possibly in response to the initial dry weather flow.
- c) The impact of mineral solids eroded from the construction site on the total SS concentrations was not estimated during these simulations with the RUNOFF block when generating surface

loadings. The observed volatile solid concentrations appear to approximately compare with the simulated total loadings although the times do not match.

- d) The BOD concentrations and mass loadings are influenced by the assumptions used for the initial catch basin loadings; however, a 40-fold increase in the catch basin mass loading increased the RUNOFF block mass output only $3\frac{1}{2}$ times.

The TRANSPORT block was analyzed briefly to find possible reasons that lead to the timing differences in resuspension of solids.

The initial bed of solids in the sewer due to the dry weather flow is generated in subroutine DWLOAD. The sedimentation criterion is based on a specific gravity of 2.7 for settleable solids, and a critical particle diameter for motion, which is determined using the sewer slope and the hydraulic radius as the parameter which depends on the amount of flow. This routine calculates the amounts of deposited and non-deposited matter for each element and for each hour, as well as subsequent resuspension at times of higher dry weather flows. The sum of deposits per day is multiplied by the number of dry days up to a maximum of half of the pipe volume.

Sediment deposition and resuspension is handled identically for the storm event simulation in subroutine QUAL. A major difference is the size of the time step, which is variable in QUAL and fixed to one hour to DWLOAD. In addition, there are other differences in the computation of the sedimentation and resuspension which appreciably influence the results of the TRANSPORT block when used with dry weather flow conditions.

Adequate analysis of this important phenomenon in sewers is essential for many system evaluations. At the same time, the problem is a very difficult one because little, if any, field data are available on sedimentation in sewers. The results of the preceding limited simulations and calibration exercise indicated that this module in the TRANSPORT model needed re-examination and re-evaluation against further field data on the occurrence and resuspension of residual sewer bottom sediment loads. One important drawback is that the above phenomenon is system-specific and depends on a large number of other external variables influencing the composition of sewer flows as percentage contributions from different parts of the watershed.

6.3.3 Quality simulation with RUNOFF block only

To isolate the difficulties associated with the inadequate modelling of the dry weather flow, a number of events covering the whole data collection period were simulated by including all of the sewer network in the RUNOFF block model.

The events modelled were:

Event	Rainfall	Remarks
May 16, 1976 a.m.	3.3 mm (0.13 in)	modelled in RUNOFF and TRANSPORT block
July 20-21, 1976	3.0 mm (0.12 in)	" " "
Sept. 17, 1976	10.6 mm (0.42 in)	Additional event

The antecedent conditions for the additional event of September 17-18, 1976, are also given in Table 8.

For these simulations, both of the available alternatives of modelling suspended solids were tested. That is a) the method initially used by Metcalfe and Eddy (designated 'special' in this analysis), and b) the procedure used for other pollutants (designated 'normal' in this analysis), which was also assumed for the combined runs discussed before. The catch basin volumes and BOD concentrations were assumed to be 20 ft³ and 200 mg/L, respectively.

The outputs of these simulations are shown in Figures 29, 30 and 31.

Using the special technique (method 1 in the figures) for the simulation of suspended solids resulted in pollutographs for the BOD concentrations which were about 40 percent higher for the May storm and were slightly different for the July and the September storms compared to the normal technique (method 0 in figures). The total BOD volumes are 10 to 20 percent higher for both the May and July storms, and about 2 percent lower in the September storm for the 'special' case. For both events, the values are lower than observed values for the two pollutants.

A long duration storm which occurred on September 17, when simulated, yielded a much lower BOD concentration than the sampled event (40 mg/L vs. 140 mg/L) in the vicinity of the storm peak, and these

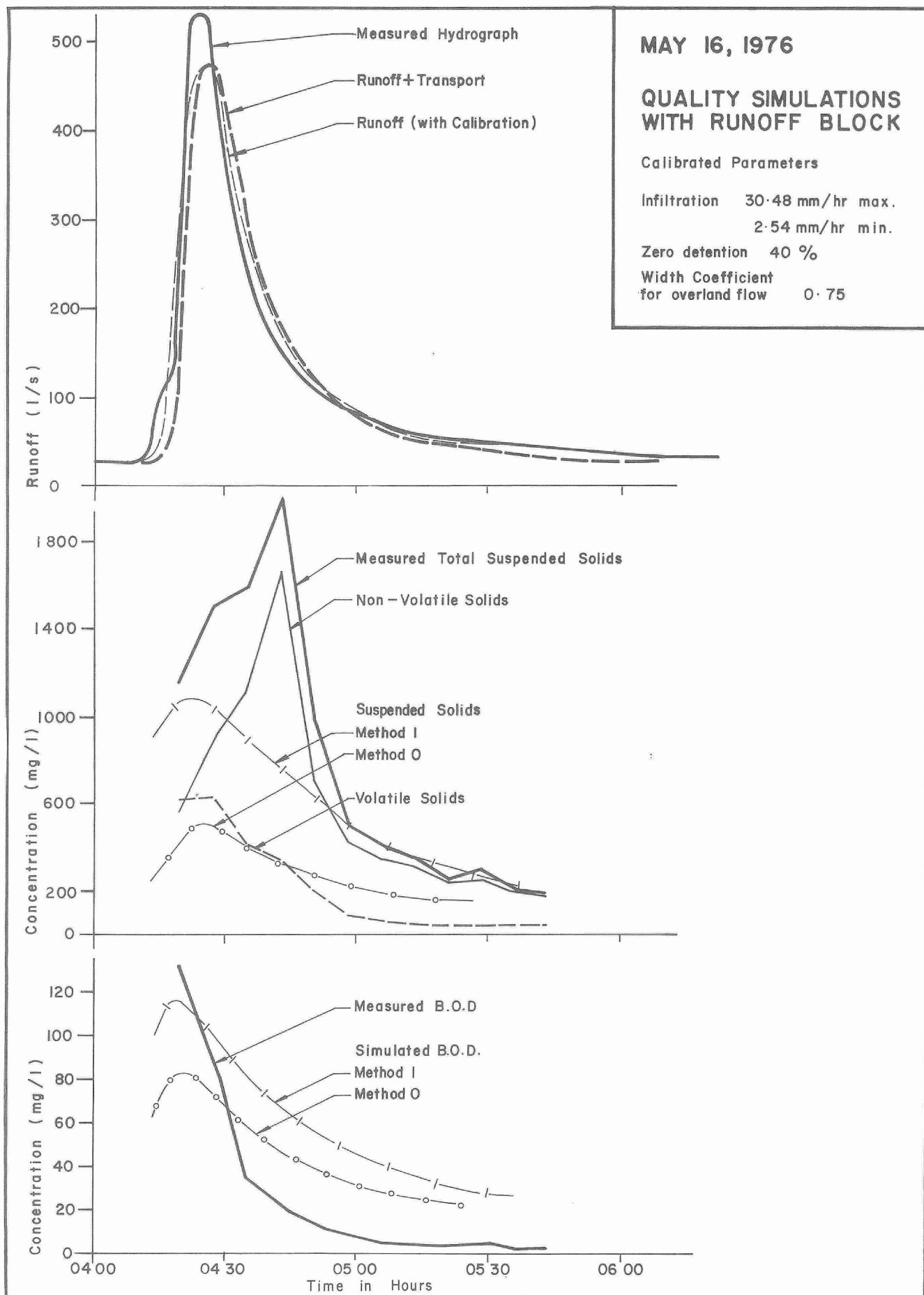


FIGURE 29. QUALITY SIMULATION WITH RUNOFF BLOCK, MAY 16, 1976

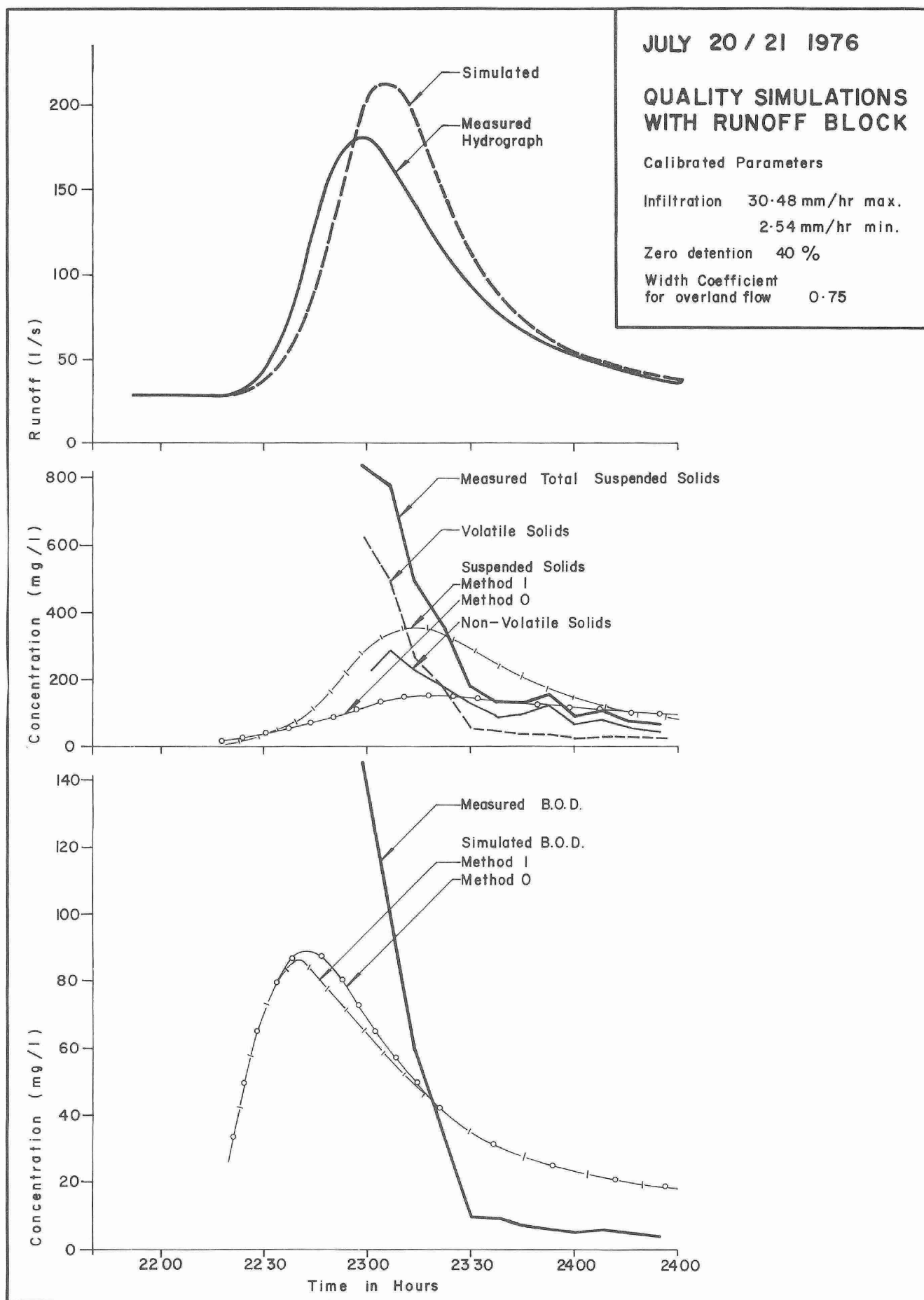


FIGURE 30. QUALITY SIMULATION WITH RUNOFF BLOCK, JULY 20-21, 1976

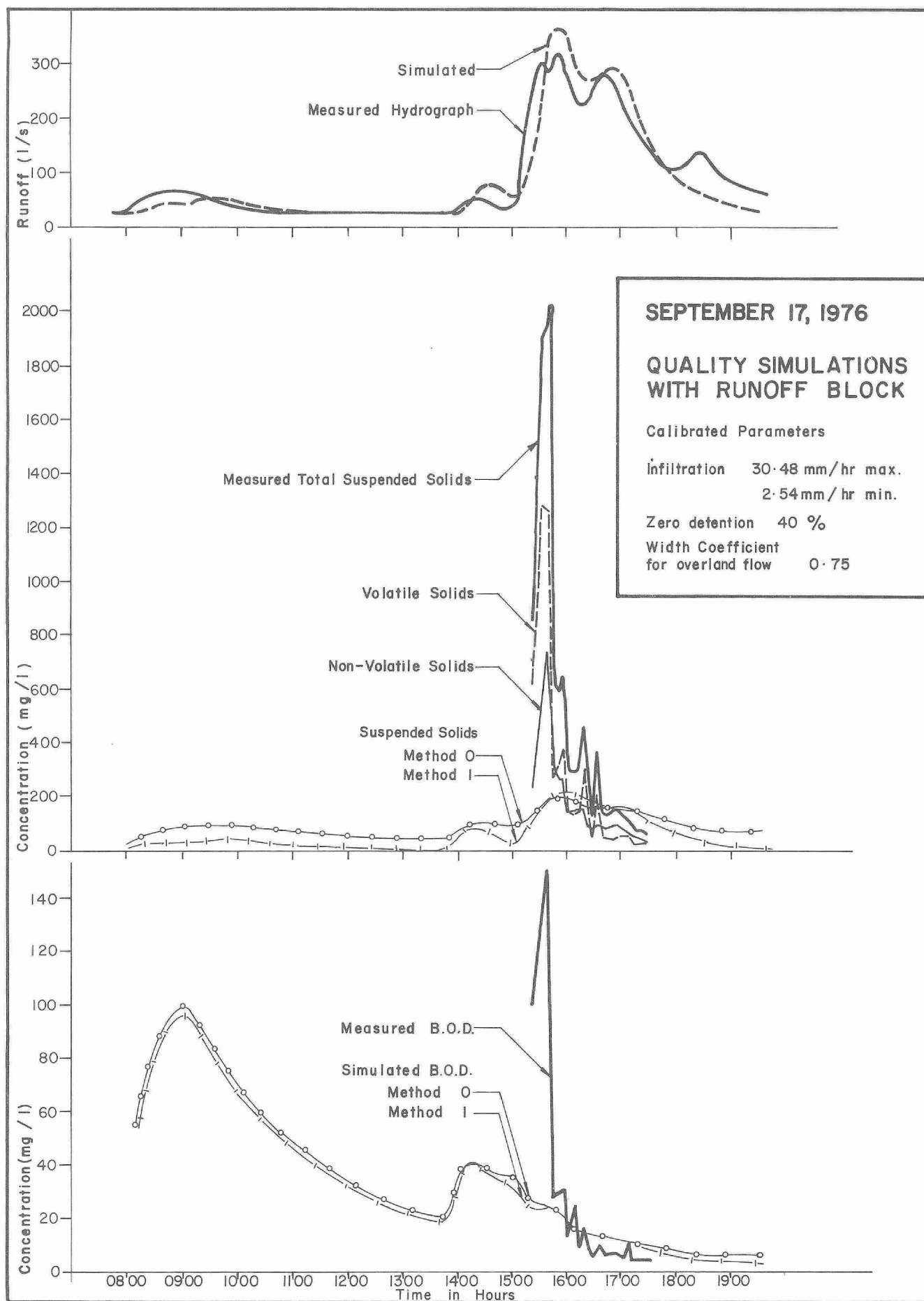


FIGURE 31. QUALITY SIMULATION WITH RUNOFF BLOCK, SEPTEMBER 17, 1976

values occurred about 90 minutes earlier than observed. In addition, the simulation provided a complete pollutograph with a peak of 100 mg/L at the beginning of the storm, for which observed results were not available.

The maximum SS concentrations indicated by the simulations did not exceed 220 mg/L, whereas the observed values were about 2000 mg/L. The influence of erosion loads from the construction site, which were not included in the model, may be partly responsible for this difference which is in the order of 10 times.

The SS concentrations varied considerably depending on the simulation technique. The special technique generally produced a more pronounced pollutograph shape with faster increase and decrease. The peak concentrations were higher and pollutograph tails showed lower concentrations, representing the measured pollutograph better than the normal technique which was used for all other pollutants.

The SS volumes obtained by the two methods were also quite different. Because of the limits of the simulation period, the figures obtained had only limited value. It can be concluded that the special technique tended to produce 50 to 100 percent more volume for two of the three events modelled (May and July), while the September event resulted in about 8 percent less volume.

The results confirmed that modelling of a combined sewer system by the RUNOFF block only does not adequately describe the amount of pollutants in the runoff, largely because of the lack of dry weather flow sediment contribution. This aspect is certainly most important after long dry periods. No attempt was made to model erosion at the construction site because it was felt that the rapidly changing conditions (excavation, sewer construction) would make the assumption of reasonable erosion coefficients difficult, if not impossible, and would, therefore, only add to the complexity of the modelling exercise.

6.3.4 Quality simulation conclusions

The attempts at calibration of the quality modelling modules using the calibrated values of variables for generating and routing surface hydrographs, and observed DWF data were unsuccessful. Possible reasons for the differences between the measured and simulated results are summarized as follows:

- a) The quality calibration objective is accurate simulation of the time variation of the pollutograph and not the total mass emissions at the end of a given event. Even though the flow hydrographs as measured and observed appear to agree fairly closely, it is not definite that the percentage contributions from different parts of the watershed (contributing different pollutant loadings) are identically modelled. Thus, these potential distribution differences, when applied to the quality model on a uniform basis, may contribute to substantial discrepancies between the pollutographs. This uncertainty can be analyzed better only if observed pollutographs and hydrographs for different points in the system are available. However, such field work would be more expensive and would further limit the practical use of the model.
- b) The persistent early occurrence of the first flush peak of simulated SS concentration curves, even before the flow hydrograph attained values beyond the initial DWF, compared to the observed times, indicated that the program consistently predicted early times for this aspect of suspended solids loadings. The concentrations predicted were also much lower than the observed values.
- c) Since the level of agreement achieved with possible variations of the pertinent default values was not encouraging, the more complex aspect of modelling of potential sediment contributions from construction sites was not attempted.
- d) For short-duration events, better agreements in the timing of BOD concentrations were achieved. However, the loading rates were again significantly less, with the RUNOFF block simulations yielding better results. The level of agreement for a longer duration was not as good.
- e) The functional forms of the equations involving the decay coefficient, etc., were not tested because the latest model version with further changes to the default values should be calibrated using more data prior to such efforts.

- f) The un-availability of specific quality calibration criteria from previous efforts was a constraint in view of the possible different directions available for proceeding with this exercise. Most earlier efforts were directed at quantity calibration of the SWMM only.

Based on the above results, the quality simulations were not extended for additional events. The more recent versions of SWMM, such as the 1977 version, have additional features such as the availability factor to account for the un-availability of a certain portion of dust and dirt for suspended solid loading production, etc. It was, therefore, strongly felt that additional modelling efforts with the version used in this study would be of very limited use for achieving the level of accuracy required when simulating the time variation of single-event pollutographs.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 General

This study dealt with three basic aspects:

- a) Selection of a test catchment and installation of a suitable instrumentation system for monitoring DWF conditions and rainfall events, and collecting data on rainfall and runoff characteristics (quantity and quality).
- b) Operation of the installed instrumentation system; gathering, processing and analyzing the above-mentioned data for a number of rainfall events.
- c) Calibration and verification of a selected version of the SWMM using the basic field data as values for input parameters and comparing the simulated results with the observed values.

Conclusions are summarized as follows:

7.2 Conclusions

- 1) The selected test catchment met most of the required criteria for collecting the pertinent physical data and the rainfall-runoff data. However, construction activity within the test catchment during part of the flow monitoring period had an adverse influence on some quality parameters, such as suspended solids.
- 2) The level of reliability of service of the instrumentation system was very good, especially during extremely adverse weather and temperature conditions. In addition, the synchronizing of different records for a given event was better than average. The automatic sampler had an inherent delay in starting which forestalled the gathering of quality data at early stages of all the recorded events. This could not be rectified during the course of the data collection period.
- 3) The dry weather flow data obtained for the watershed was not sufficient to obtain the relevant average values for quantity and quality parameters. The installed flow measuring system was not adequately sensitive to accurately measure these flows. The measuring weir installed across the trunk sewer possibly changed

the normal deposition and resuspension pattern of the dry weather flow pollutants.

- 4) A reliable record of rainfall and runoff data was compiled for a number of events covering a broad range of rainfall volumes for this test catchment.
- 5) The sample collection program suffered from the delays in starting of sampling which resulted in incomplete pollutographs (as mentioned earlier), thus preventing the calculation of mass loads.
- 6) The two rain gauge records demonstrated the aerial variation of rainfall; this was further strengthened by the increased deviation of simulated results from observed values when the record of one gauge was not considered for modelling.
- 7) The variations between the simulated and observed results for the initial SWMM quantity modelling, when studied, furnished valuable information, especially helpful in view of the large number of input data variables involved, to formulate the calibration methodology.
- 8) The calibration efforts confirmed the importance of the use of RUNOFF block input variables as calibration parameters. To achieve a calibration result of wider application, it was advantageous to use the results of a number of events rather than a single event.
- 9) The observed runoff volumes for longer duration high volume rainfalls were found to be significantly increased by extraneous inflows into the sewers other than DWF and surface runoff contributions. The base flows for such events were evaluated by a subjective extension of antecedent flows during the calibration efforts.
- 10) If calibration is based on the requirement of closer agreement of results for higher rainfall events, then the model will furnish an upper level limiting curve of runoff volumes for a range of events including lower rainfall values during verification. These results tend to agree most closely with observed thunderstorm events, which is of more practical value.

- 11) The initial analysis of observed pollutographs generally showed the "first flush" in storm water runoff. The influence of the antecedent dry period in determining the pollutant concentrations was evident for a number of events. Construction activity substantially increased the suspended solid loading. The effect of resuspension of sewer deposits was evident from the initially high volatile solids loading rates.
- 12) The attempts at calibrating the quality modules resulted in inadequate levels of agreement for a number of events (pollutants BOD and SS, which are vital indicators of storm water pollution) with very conservative assumptions for default values. The net indicative conclusion of these efforts is that any additional modelling should be attempted only on the latter versions of the quality model, as the discrepancies encountered in the present attempt with the earlier version are not encouraging.

7.3 Recommendations

On the basis of the experience gained during the course of this study and the conclusions derived from the analysis of the results, a few recommendations are summarized for consideration in similar future studies.

- 1) The test catchment should have a stabilized land use pattern; otherwise, specific facilities to monitor varying land use conditions such as excavation or land fill activity, etc., should be part of the data collection system, to establish the special characteristics, mainly for quality aspects, of such changes.
- 2) If feasible, for watersheds larger than say 100 acres, an additional rain gauge in the watershed will be of considerable benefit in establishing the influence of aerial variation of rain on an event basis.
- 3) The automatic sampler operation must be modified to cover the early stages of runoff events. Supplemental manual grab sampling by field staff, especially during long-duration storms, will be of significant use for data correlation and subsequent quality calibration work, especially for mass loading estimates as related to runoff volumes generated by each event.

- 4) Better data for sewer infiltration inflows due to causes such as antecedent rains or snow melting, etc., must be obtained, or the influence of these extraneous flows, especially for combined sewers, must be established, preferably on a seasonal basis to understand their relative importance for quantity and quality modelling studies.
- 5) The data gathered in this study have substantial potential for future use in calibration of other models, especially the quantity aspects.
- 6) The results of quantity and quality calibration efforts can be used for better defining the calibration criteria and the methodology of calibration of SWMM.
- 7) It is recommended that the techniques of pre-storm simulation of dry weather flow sedimentation by the TRANSPORT block and the simulation of pollutant wash-off from surface by the RUNOFF block be re-examined on the basis of the present limited results.

LIST OF ABBREVIATIONS

ac	- acres	km/h	- kilometres per hour
BOD	- biochemical oxygen demand	L	- litres
COD	- chemical oxygen demand	L/s	- litres per second
cfs	- cubic feet per second	lb/min	- pounds per minute
cm	- centimetres	m	- metres
DD	- dust and dirt	m ³	- cubic metres
ft	- feet	m ³ /ha	- cubic metres per hectare
ft/s	- feet per second	m ³ /s	- cubic metres per second
ft ³	- cubic feet	mm	- millimetres
ft ³ /ac	- cubic feet per acre	mm/h	- millimetres per hour
g/min	- grams per minute	mph	- miles per hour
g/person/d	- grams per person per day	mg/L	- milligrams per litre
ha	- hectares	ppa	- persons per acre
h	- hour	SS	- suspended solids
in	- inches	TOTSS	- total suspended solids
km	- kilometres		

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STAFF OF GORE AND STORRIE LIMITED

The following engineering staff of Gore and Storrie Limited were responsible for the instrumentation of the test catchment, collection and analysis of the data, and the preparation of this report:

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Sudu Vatagodakumbura, P.Eng - Project Manager

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